CONTENTS

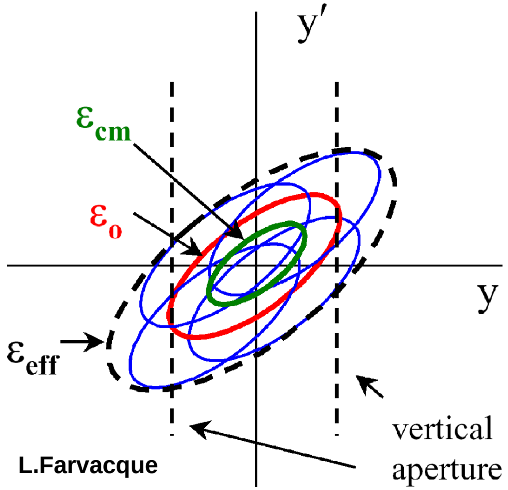
It's a long way to go ...

INTRODUCTION

Table 1: Typical stability requirements for selected measurement parameters common to a majority of experiments (Courtesy R. Hettel)

Measurement parameter	**Stability requirement**
Intensity variation $\Delta I/I$	$<$0.1 % of normalized I
Position and angle accuracy	$<$1 % of beam σ and σ'
Energy resolution $\Delta E/E$	$<$0.01 %
Timing jitter	$<$10 % of critical t scale
Data acquisition rate	$\approx 10^{-3}$-10^{5} Hz
Stability period	$10^{-2(3)}$-10^{5} sec

$\Rightarrow$ **Stabilization of the electron beam in its 6D phase space to meet stability requirements for the photon beam parameters. Effect of photon beam instability on flux depends on the time scale of the fluctuation τ_f relative to the detector sampling and data integration times τ_d:**



- $\underline{\tau_d \gg \tau_f}$:
  $\epsilon_{\text{eff}} = \epsilon_0 + \epsilon_{\text{cm}}$:
  Motion of $\approx$**30 %** of σ and σ'
  $\Rightarrow$ *smeared out*
  $\Rightarrow$ **10 %** increase in ϵ_{eff}
- $\underline{\tau_d \ll \tau_f}$:
  $\epsilon_{\text{eff}} \approx \epsilon_0 + 2\sqrt{\epsilon_0 \epsilon_{\text{cm}}} + \epsilon_{\text{cm}}$:
  Motion of $\approx$**5 %** of σ and σ'
  $\Rightarrow$ *new measurement noise*
  $\Rightarrow$ **10 %** increase in ϵ_{eff}

INTRODUCTION

Since most 3rd generation light sources feature:

- **low beta ($\approx$1 m) straights** (SOLEIL: $\approx$1.8 m) in order to allow for
- **low gap ($<$10 mm) insertion devices (IDs)** (SOLEIL: U20: 5.5-70 mm)

and operate at:

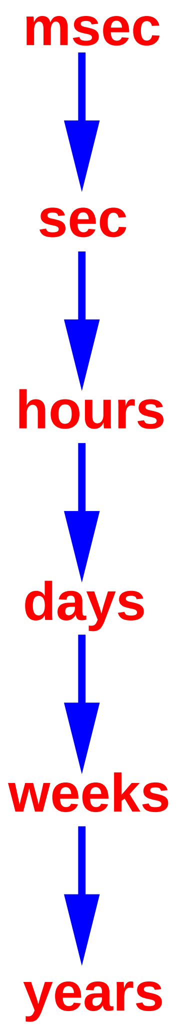
- **small emittance coupling $<$1% (SLS: $<$3 pm·rad/5.5 nm·rad=0.06%)** with
- **horizontal design emittances of just a few ($<$10 nm·rad**)
(SOLEIL: 3.73 nm·rad @ 2.75 GeV)

the requirements compiled in Table 1 lead to:

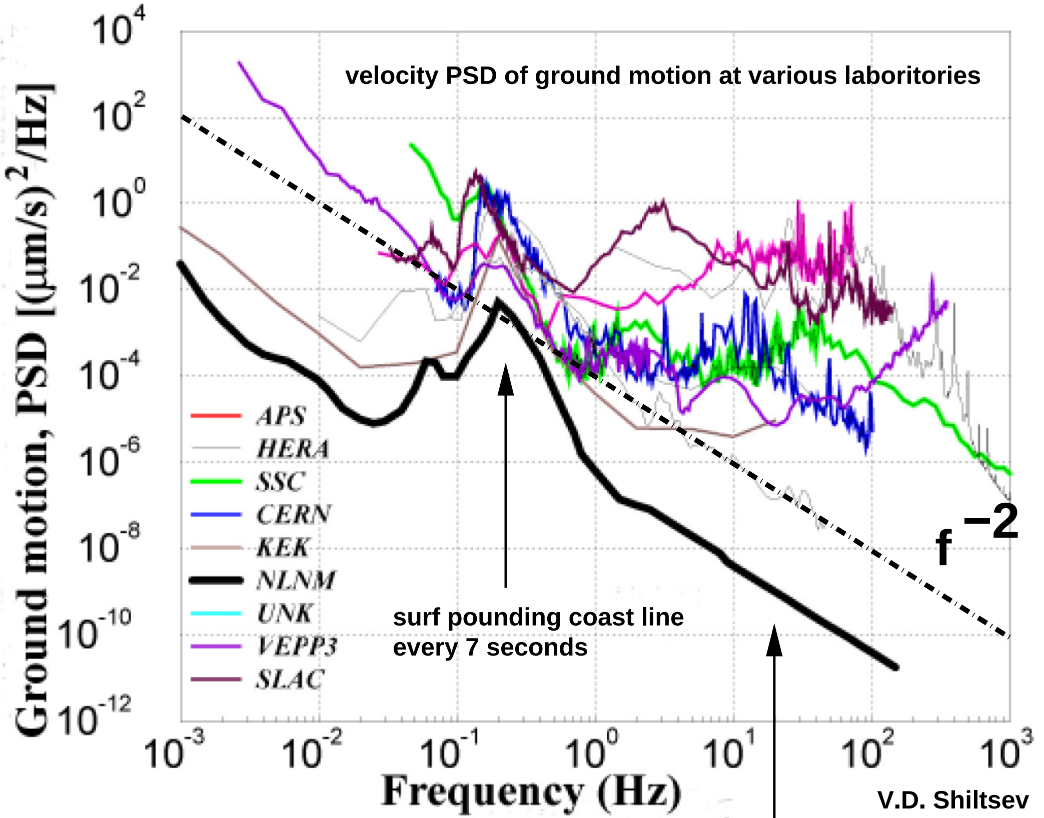
- **sub-micron tolerances for the vertical positional and angular stability of the electron beam @ the ID source points** over a large frequency range **Δf: 10^{-5}-$10^{2(3)}$ Hz** (timescale: msecs - hours/days):
- σ_{cm} **$<1\mu$m** (SOLEIL: $<0.8\mu$m) and σ'_{cm} **$<1\mu$rad** (SOLEIL: $<0.5\mu$rad)

NOISE SOURCES

- **Short term ($<$1 hour):**
  Ground vibration induced by human activities, mechanical devices like compressors and cranes or external sources like road traffic potentially attenuated by concrete slabs, amplified by girder resonances and spatial frequency dependent orbit responses, ID changes (fast polarization switching IDs $<$100 Hz), cooling water circuits, power supply (PS) noise, electrical stray fields, booster operation, slow changes of ID settings, “top-up” injection. Sources of beam motion associated with synchrotron oscillations and single- and coupled bunch instabilities are not considered.
- **Medium term ($<$1 week):**
  Movement of the vacuum chamber (or even magnets) due to changes of the synchrotron radiation induced heat load especially in decaying beam operation, water cooling, tunnel and hall temperature variations, day/night variations, gravitational sun/moon earth tide cycle.
- **Long term ($>$1 week):**
  Ground settlement and seasonal effects (temperature, rain fall) resulting in alignment changes of accelerator components including girders and magnets.


msec
sec
hours
days
weeks
years

SHORT TERM STABILITY - Ground Motion

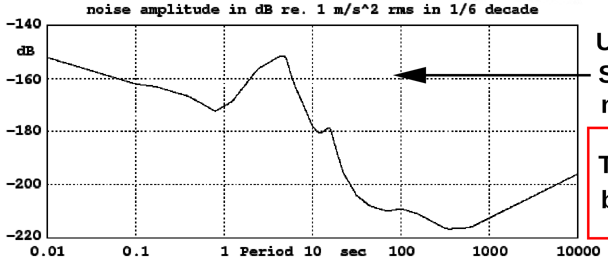


velocity PSD of ground motion at various laboritories

surf pounding coast line
every 7 seconds

f^{-2}

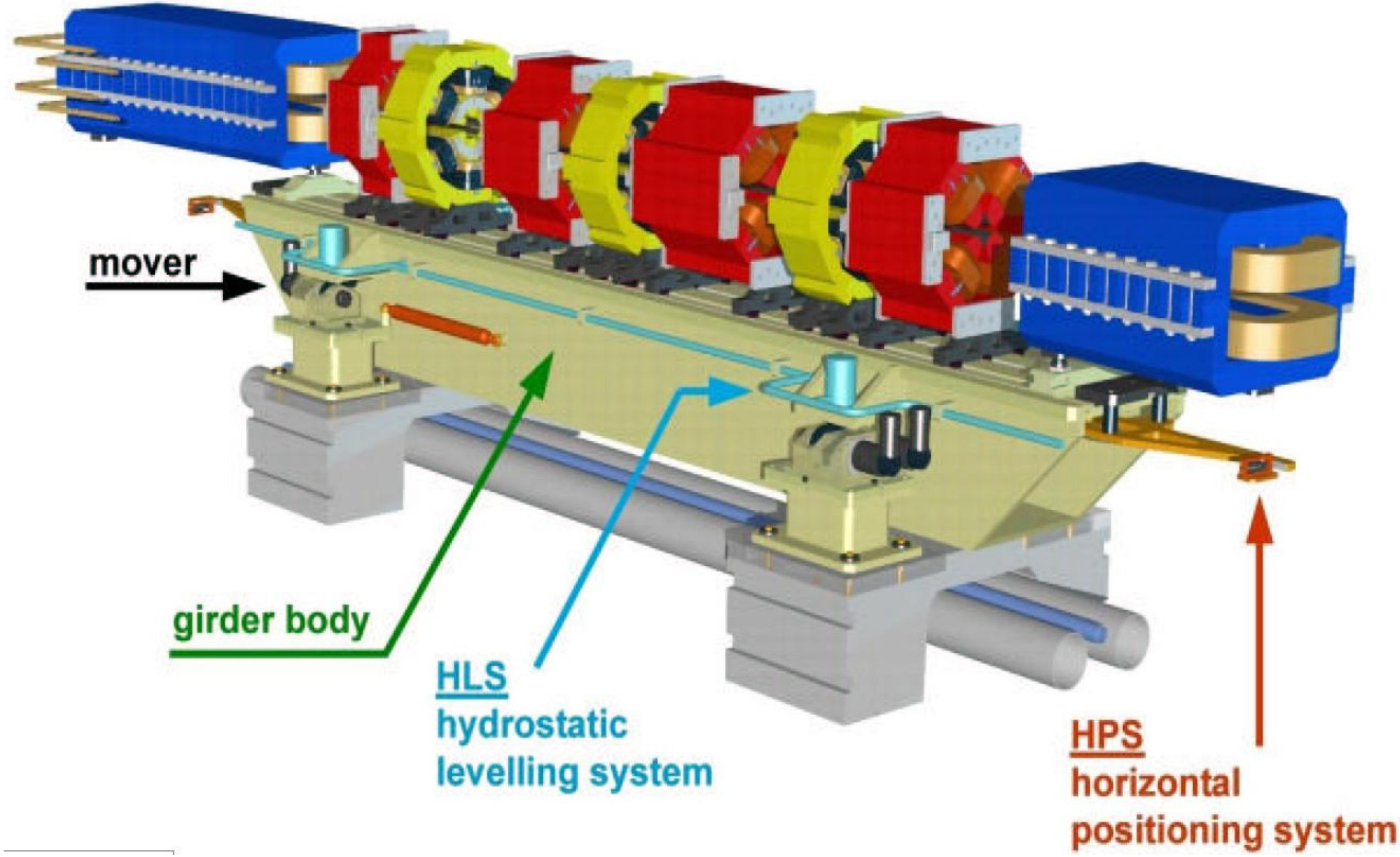
V.D. Shiltsev



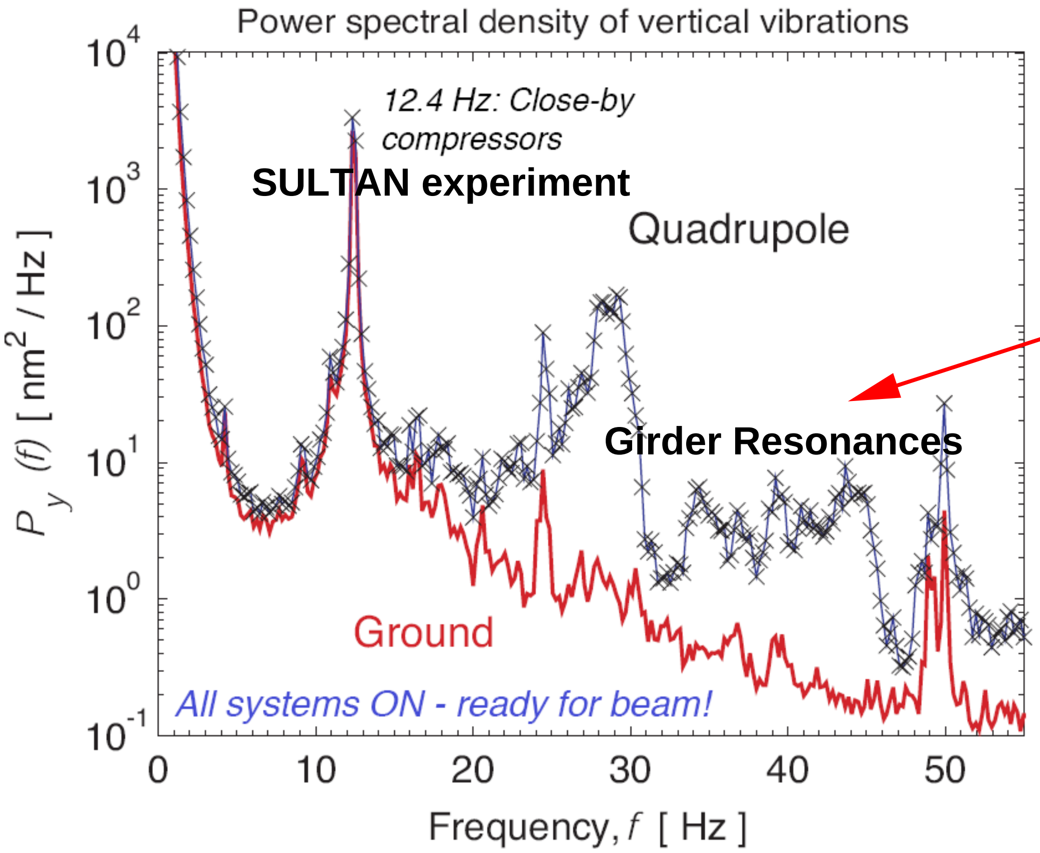
USGS New Low Noise Model (NLNM):
Summarizes the lowest observed seismic
noise levels throughout the freq. band

The PSD in position drops of faster
by a factor of f^{-2} –> f^{-4}

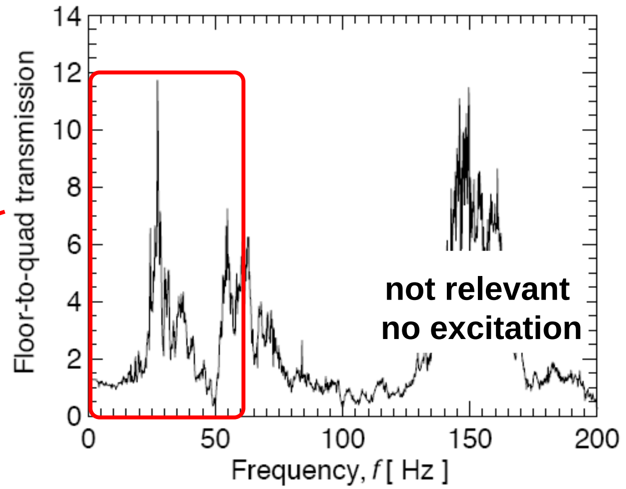
SHORT TERM STABILITY - Girder Design (*SLS*)

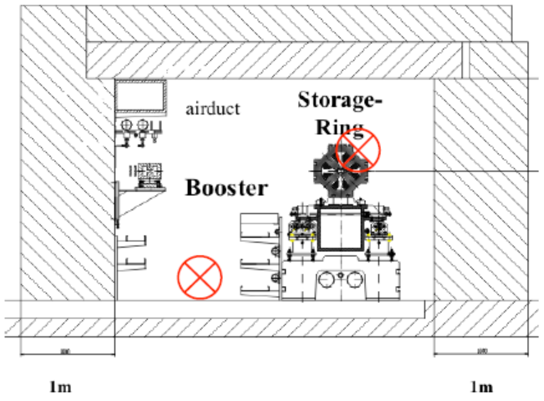


SHORT TERM STABILITY (*SLS*)



Transmission = amplification of GM due structural resonances of girder and quad.





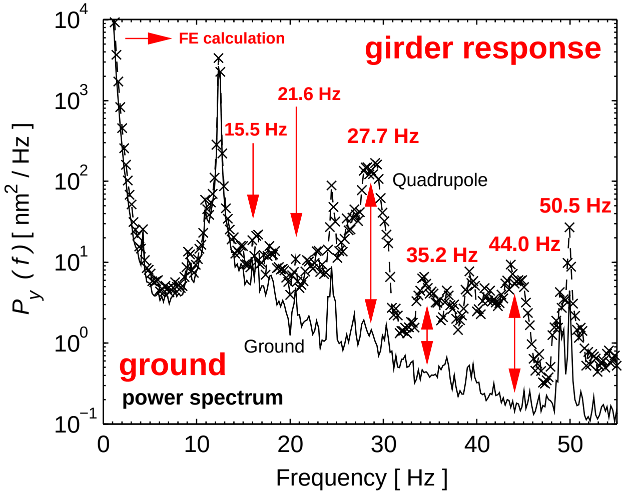
S. Redaelli

Overall motion above 4 Hz: ***Floor → ~ 30 nm***

Quad → ~ 50 nm

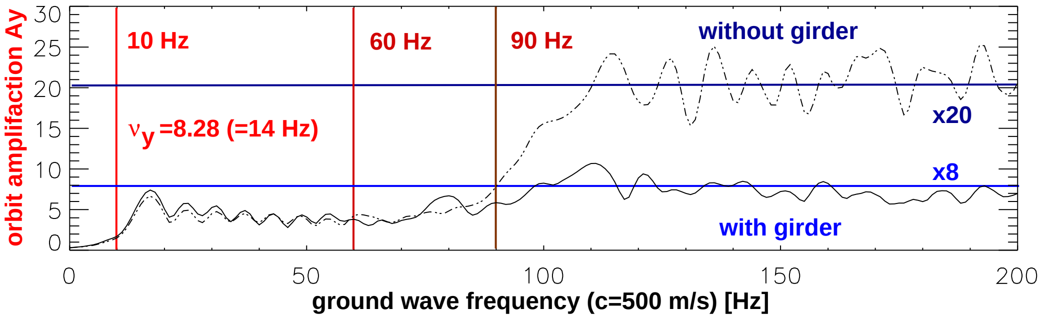
SHORT TERM STABILITY (*SLS*)

f [Hz]	Noise Source
3	**booster stray fields**
12.4	helium-refrigerator
15-50	**girder resonances**
50	**power supplies&pumps**

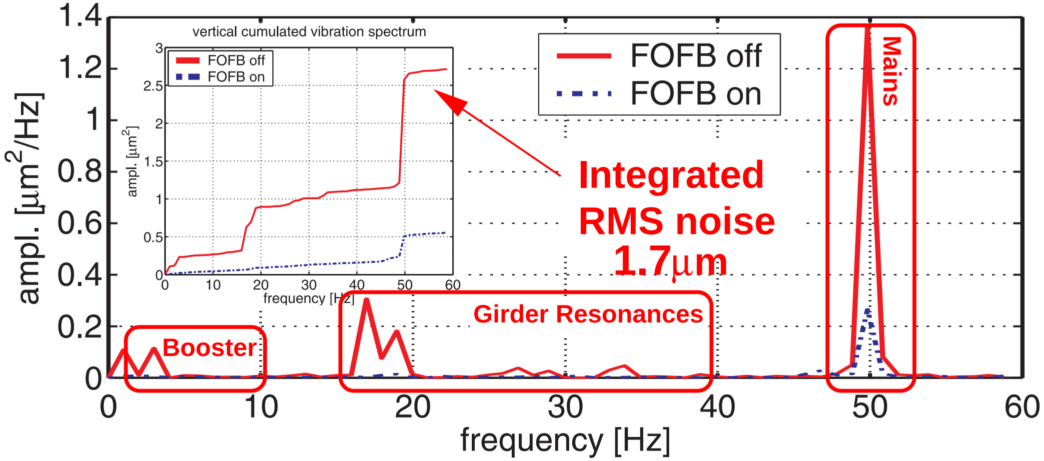


Vertical **vibration** PSD (1-55 Hz) measured on the slab and a girder (S. Redaelli).

Vertical **orbit amplification factor** A_y for planar waves:

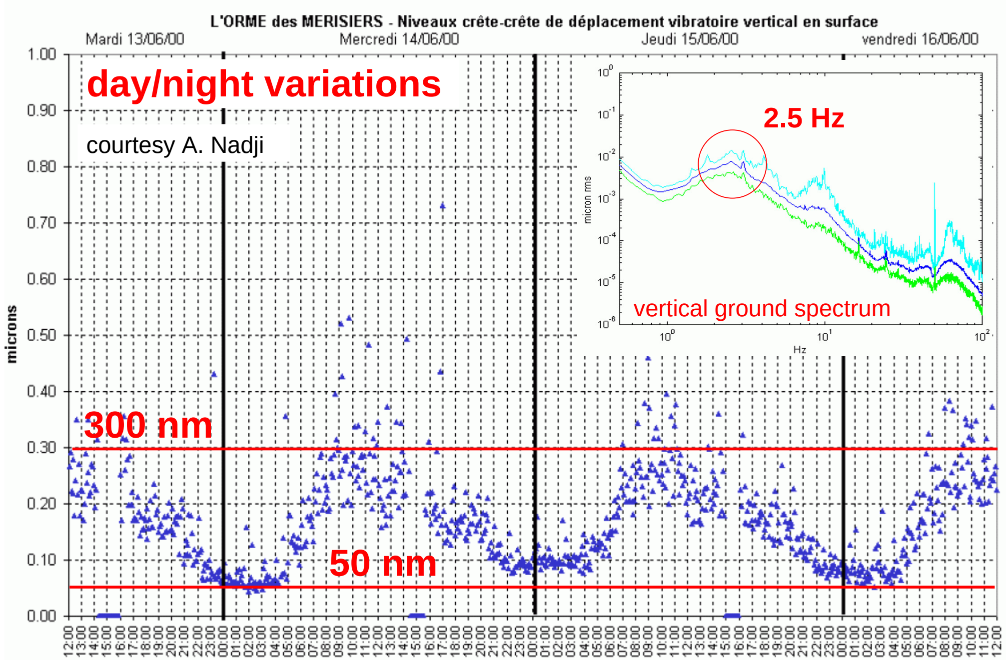


Vertical **orbit** PSD (1-60 Hz) without and with orbit feedback @ BPM (β_y=18 m) (T. Schilcher):



⇒ **Integrated RMS motion σ_y only ≈0.4 μm $\cdot\sqrt{\beta_y}$!**

SHORT TERM STABILITY (*SOLEIL*)



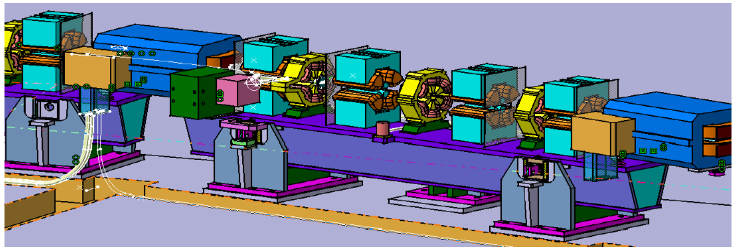
Vertical day/night variations and ground **vibration** spectrum (≈1-100 Hz) ⇒ **planar wave @ 2.5 Hz with amplitude 800 nm peak-to-peak !**

Reason: trucks with **suspension resonance frequencies of ≈2.5 Hz** (close to typical frequency of the ground) on nearby roads going typically @ 60 km/h (⇒ repair of the paving).

Orbit Ampl.	A_x	A_y
Without girders	30	10
With girders	16	3
Reduction	**1.9**	**3.3**

Careful girder design:

- **3 jacks** (removed in final design)
- 4 supports in upper part of girder
- **No** rc'ed girder movers (⇒ SLS)

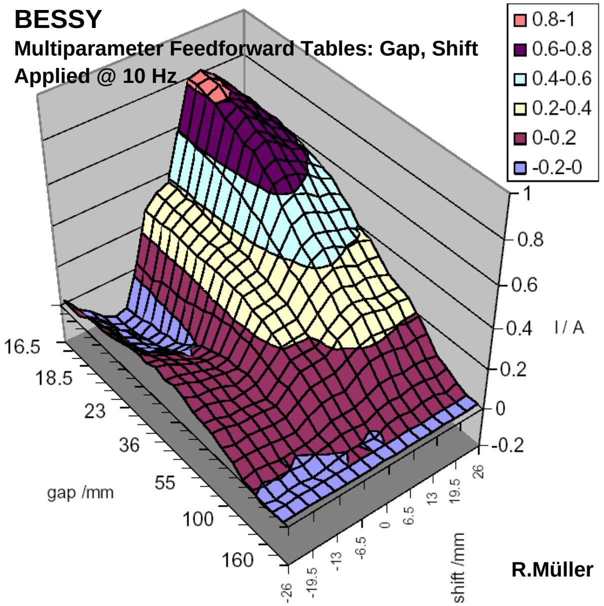


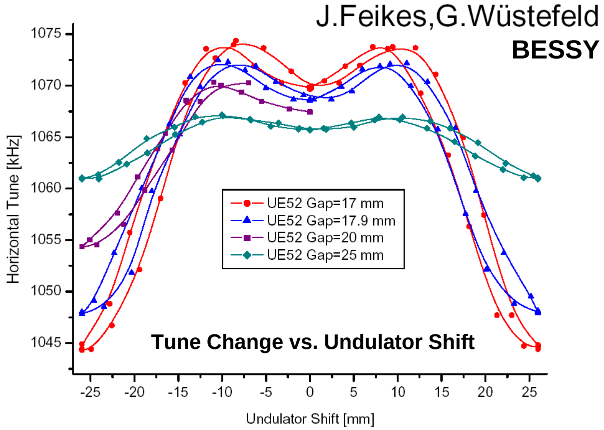
Eigenmodes	**1st**	2nd	3rd
f [Hz]	**46.8**	47	54

⇒ **No amplification of planar wave !**

J.M. Filhol

SHORT TERM STABILITY





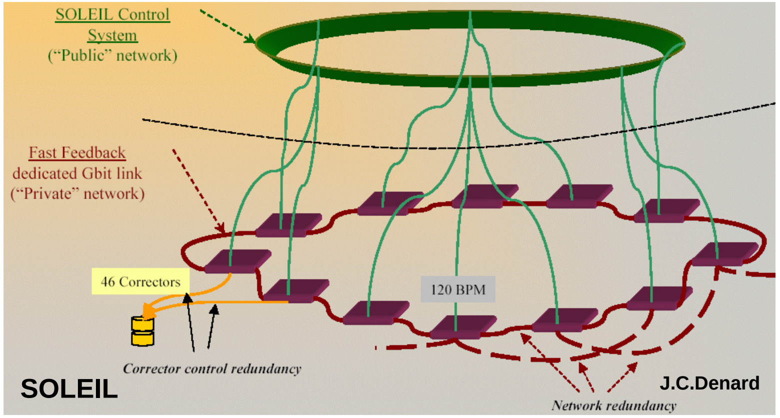
This suggests that **a proper mechanical design can assure short term orbit stability on the micron or even sub-micron level**. Thus the **operation of the installed IDs becomes the dominant contribution to the short term noise**. Since most of the disturbances are of systematic nature and therefore reproducible, **feed-forward correction tables can help to minimize the perturbation**.

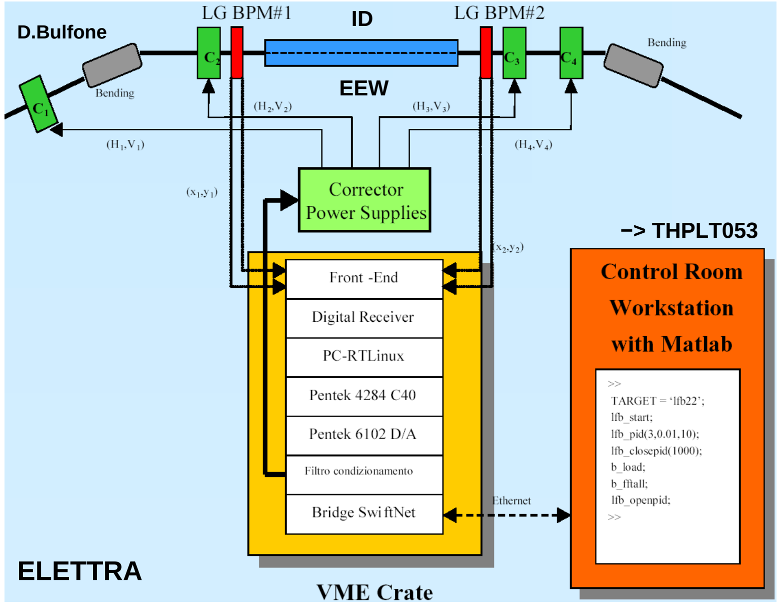
Nevertheless the remaining noise is significant and needs to be attenuated by orbit feedback systems featuring large correction bandwidths $>$100 Hz !

SHORT TERM STABILITY - Orbit Feedbacks

Orbit feedbacks can be divided in two classes:

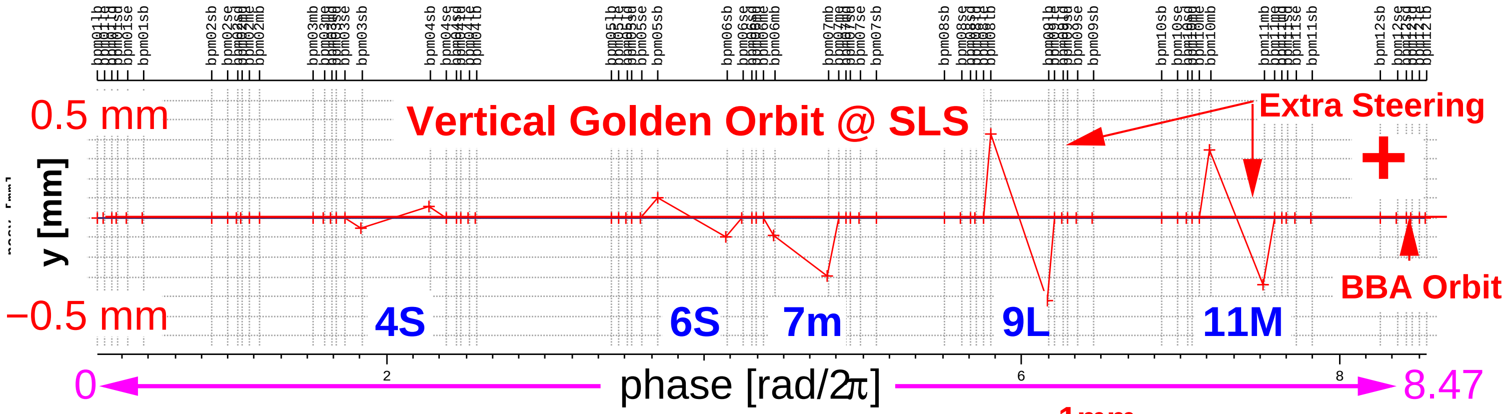
- **Global feedbacks** compensate for perturbations generated by all IDs based on global orbit and/or photon beam positions by means of global correction.
- **Local feedbacks** compensate for perturbations generated by individual IDs based on local orbit and/or photon beam positions by means of local correction in the vicinity of the IDs.

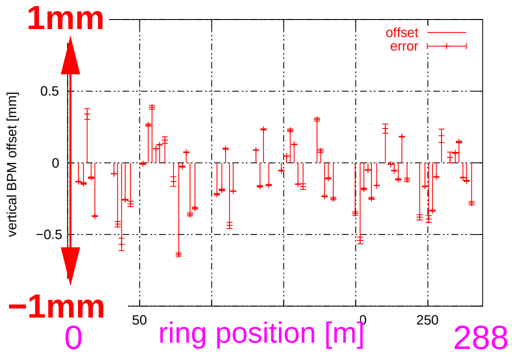




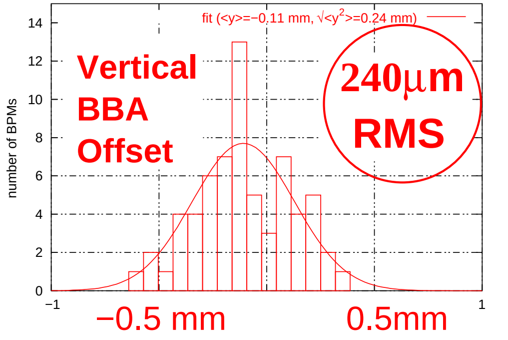
```
>>
 TARGET = ‘lfb22’;
 lfb_start;
 lfb_pid(3,0.01,10);
 lfb_closepid(1000);
 b_load;
 b_fftall;
 lfb_openpid;
>>
```

SHORT TERM STABILITY - BBA/Golden Orbit





Golden Orbit: goes through centers of quadrupoles and sextupoles in order to minimize optics distortions leading to spurious vertical dispersion and betatron coupling (emittance coupling) + extra steering @ IDs



Beam−based alignment (BBA) techniques to find offset BPM − adjacent quadrupole center

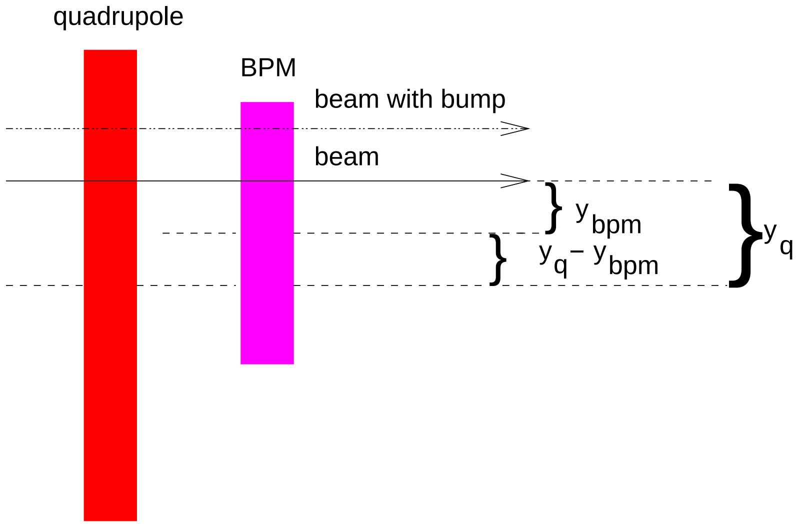
alter focusing of individual quadrupoles, resulting RMS orbit change is proportional to initial orbit excursion at location of quadrupole.

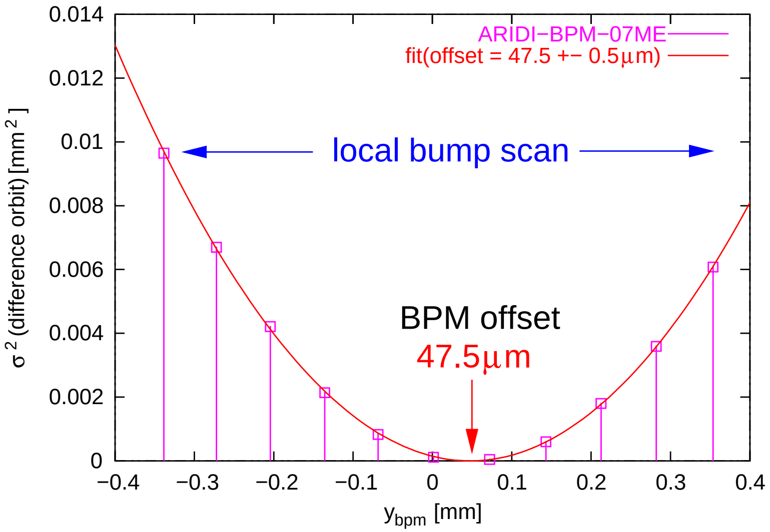
BBA offset = convolution of mechanical and electronical properties of BPM

RMS offset even for well aligned machines >100µ m !

DC RMS corrector strength reduced when correcting to BBA orbit !

SHORT TERM STABILITY - How is the position of BPMs measured ?



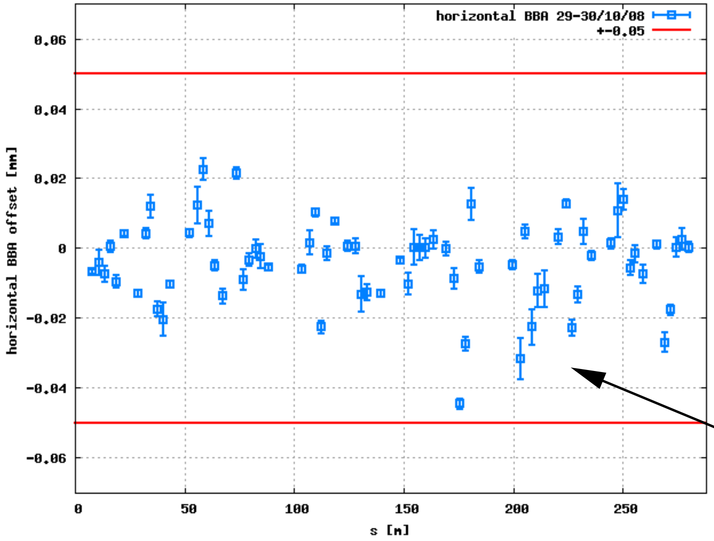


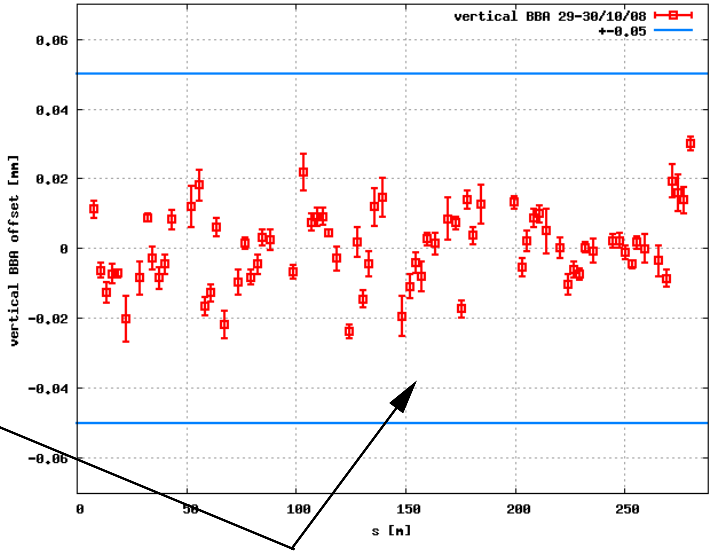
The so-called “Beam-Based Alignment” (BBA) (with respect to quadrupoles) technique is based on the fact that if the strength of a single quadrupole q in the ring is changed, the resulting difference in the closed orbit $\Delta y(s)$ is proportional to the original offset y_q of the beam at q:

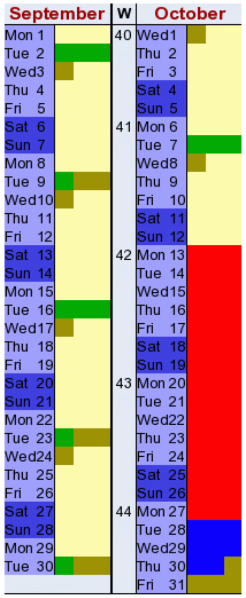
$$\Delta y''(s) - (k(s) + \Delta k(s))\Delta y(s) = \Delta k(s) y_q(s).$$

The difference orbit is thus given by the closed orbit formula for a single kick, but calculated with the perturbed optics including $\Delta k(s)$. From the measured difference orbit the kick and thus y_q can be easily determined and compared to the nominal orbit y_{bpm} in the BPM adjacent to the quadrupole, yielding the offset between BPM and quadrupole axis. The error of the position y_{bpm} is given by the resolution of the BPM system (Method can also be applied to sextupoles).

SHORT TERM STABILITY - Beam-Based Alignment (BBA) Measurements (*SLS*)

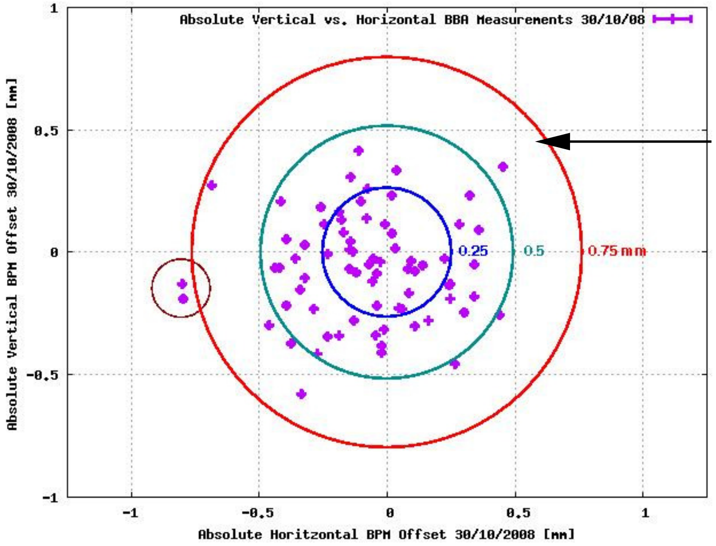






September	W	October
Mon 1	40	Wed1
Tue 2		Thu 2
Wed3		Fri 3
Thu 4		Sat 4
Fri 5		Sun 5
Sat 6	41	Mon 6
Sun 7		Tue 7
Mon 8		Wed8
Tue 9		Thu 9
Wed10		Fri 10
Thu 11		Sat 11
Fri 12		Sun 12
Sat 13	42	Mon 13
Sun 14		Tue 14
Mon 15		Wed15
Tue 16		Thu 16
Wed17		Fri 17
Thu 18		Sat 18
Fri 19		Sun 19
Sat 20	43	Mon 20
Sun 21		Tue 21
Mon 22		Wed22
Tue 23		Thu 23
Wed24		Fri 24
Thu 25		Sat 25
Fri 26		Sun 26
Sat 27	44	Mon 27
Sun 28		Tue 28
Mon 29		Wed29
Tue 30		Thu 30
		Fri 31

Changes of BBA constants after 2 months of operation and 2 weeks of shutdown (changes stay within a +−50 um band)



Absolute BBA constants which feature offsets of more than

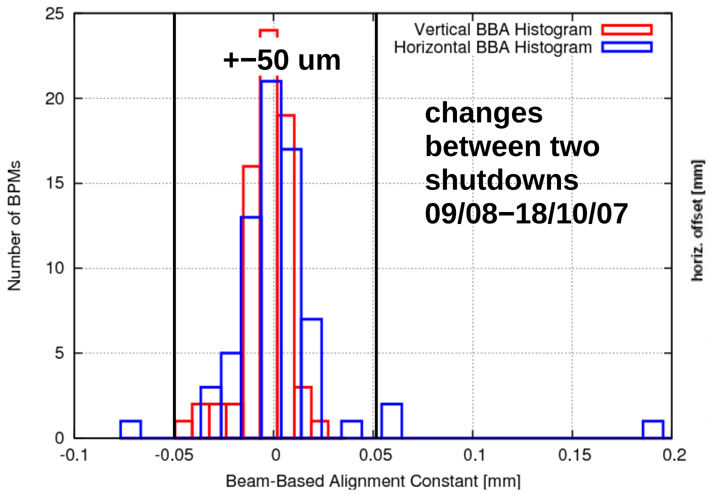
750 um !

These large offsets are of electronical origin and mechanical origin (vacuum chambers are floating with respect to the quadrupole centers).

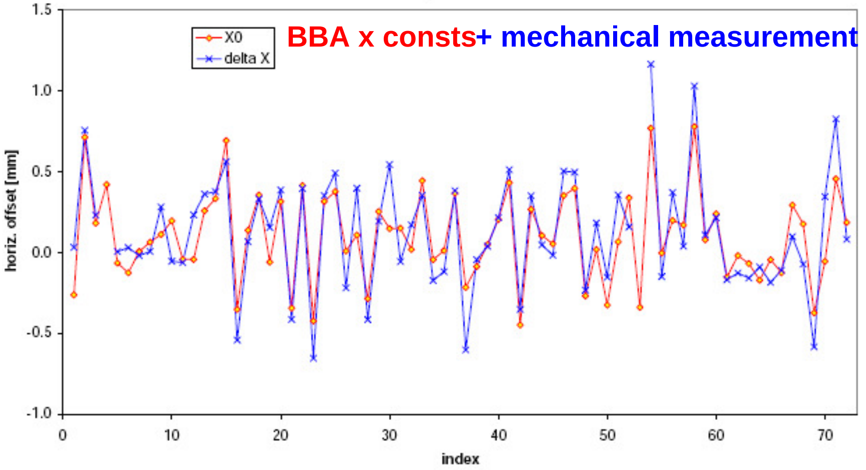
How to destinguish between the two contribution ?

SHORT TERM STABILITY - Comparing BBA with Mechanical Meas. (*SLS*)

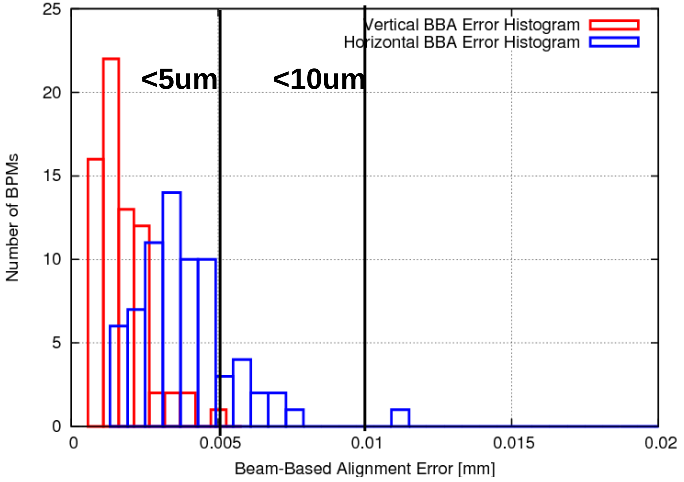
BBA dx/dy histograms for the SLS



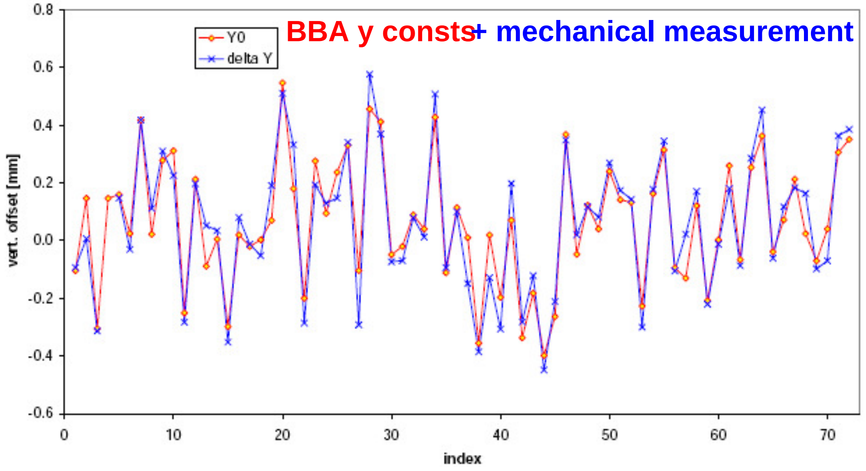
BPM horizontal offsets X0
and measured displacement delta X



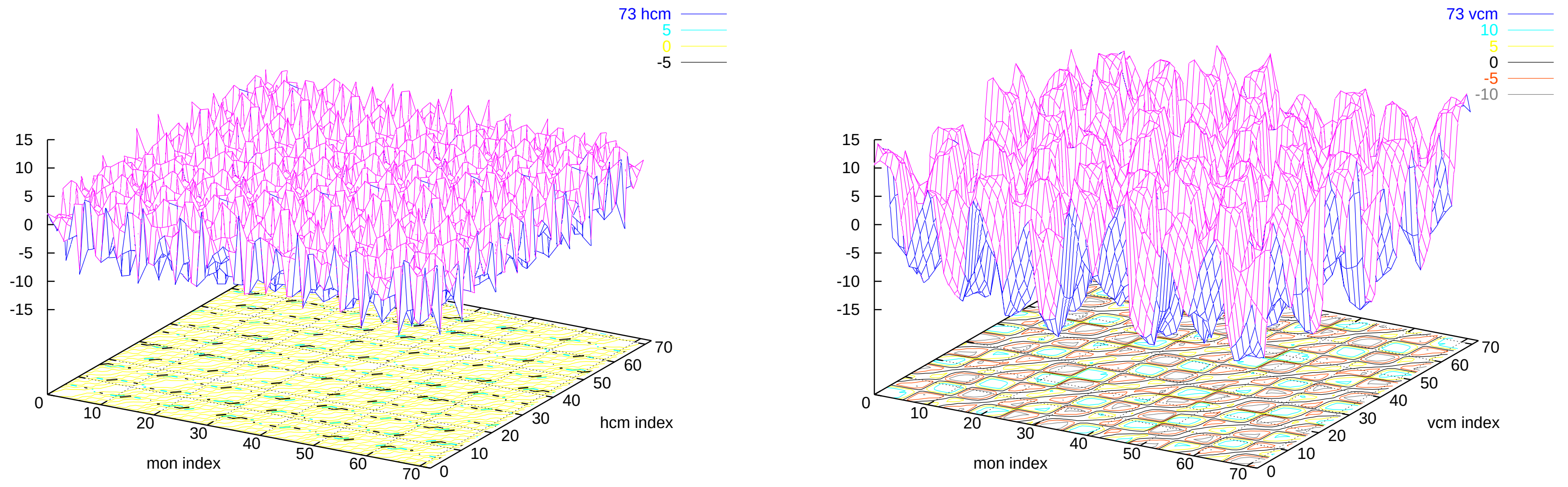
BBA dx/dy error histograms for the SLS



BPM vertical offsets Y0
and measured displacements delta Y



SHORT TERM STABILITY - Corrector / BPM Response Matrices (*SLS*)

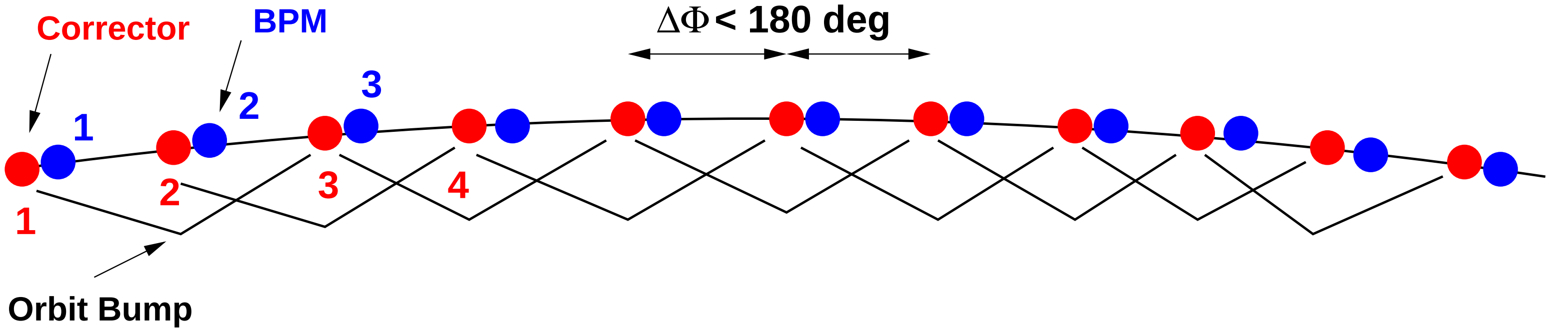


$$A_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi\nu} \cos\left[\pi\nu - |\phi_i - \phi_j|\right]$$

- “Response Matrix”: Differences from the “Closed Orbit” (“Difference Orbit”) due to a kick of corrector i are recorded at BPM positions $j = 1..73$.
- ν_x = 20.44 (≈3 BPMs/Correctors per unit phase, $\phi = \int_0^s 1/\beta(s)ds$)
- ν_y = 8.74 (≈9 BPMs/correctors per unit phase)

SHORT TERM STABILITY - How is a Closed Orbit corrected ?

- **Sliding Bump** - Phase advances between Correctors $0^\circ < \Delta\phi < 180^\circ$, Correctors 1,2,3 allow to zero the orbit in BPM 2 near Corrector 2. 1 opens "Orbit Bump", 2 provides kick for 3 to close it again. Continue ("Slide") with 2,3,4 to zero orbit in BPM 3 ... iterate until orbit is minimized in all BPMs !



- **MICADO** - Finds a set of "Most Effective Correctors", which minimize the RMS orbit in all BPMs at a minimum ("most effective") RMS Corrector kick by means of the SIMPLEX algorithm. The number of Correctors (= iterations) is selectable.

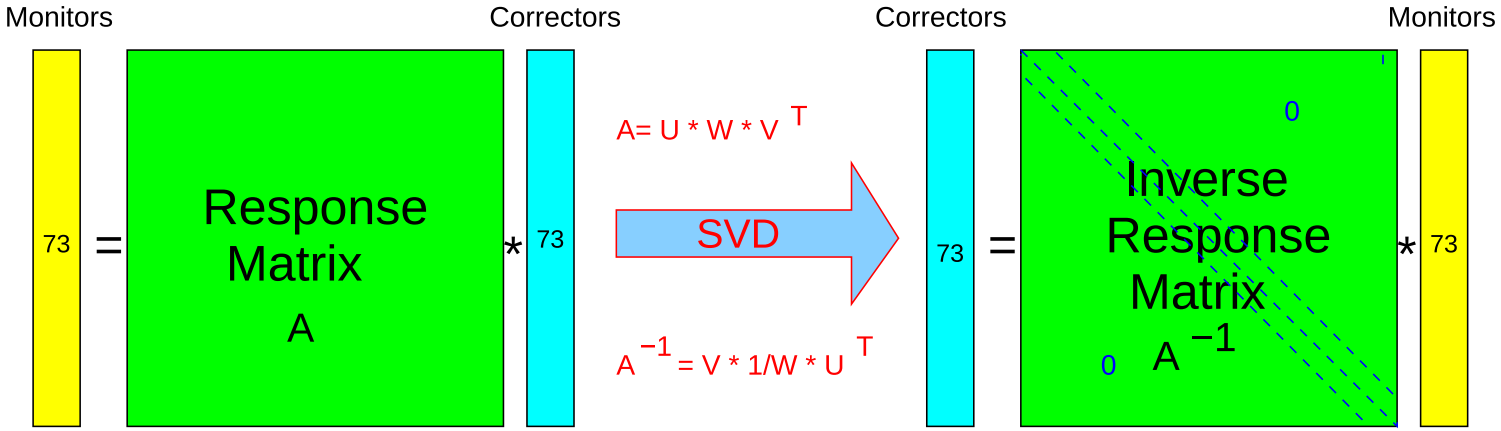
- **Singular Value Decomposition (SVD)** - Decomposes the "Response Matrix"

$A_{ij} = \frac{\sqrt{\beta_i\beta_j}}{2\sin\pi\nu}\cos\left[\pi\nu - |\phi_i - \phi_j|\right]$ containing the orbit "response" in BPM i to a change of Corrector j into matrices U,W,V with $A = U * W * V^T$. W is a diagonal matrix containing the sorted Eigenvalues of A. The "inverse" correction matrix is given by $A^{-1} = V * 1/W * U^T$.

SVD makes the other presented schemes obsolete !-)

SHORT TERM STABILITY - What is SVD doing ?

73 monitors / 73 correctors

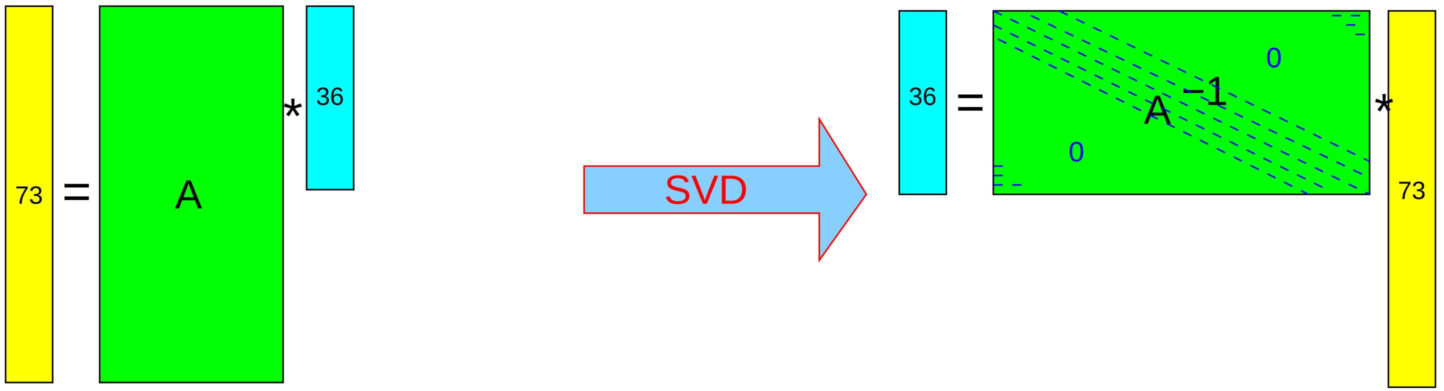


$A = U * W * V^T$

$A^{-1} = V * 1/W * U^T$

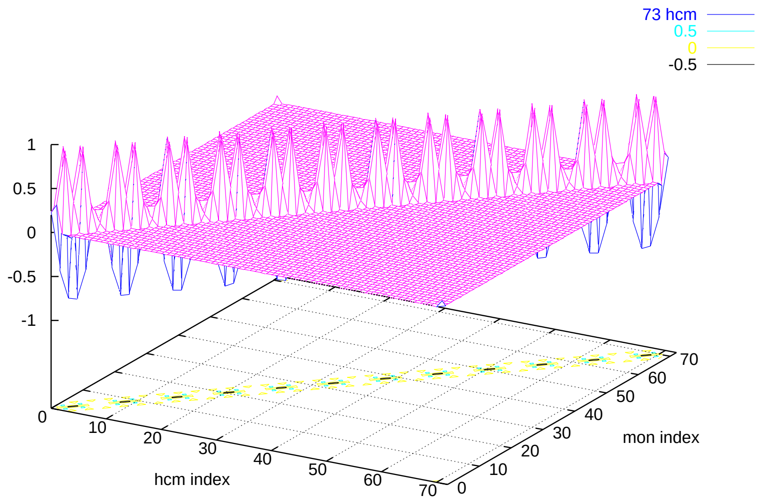
=> Minimization of the RMS orbit (=0 in case of "Matrix Inversion" using all Eigenvalues)

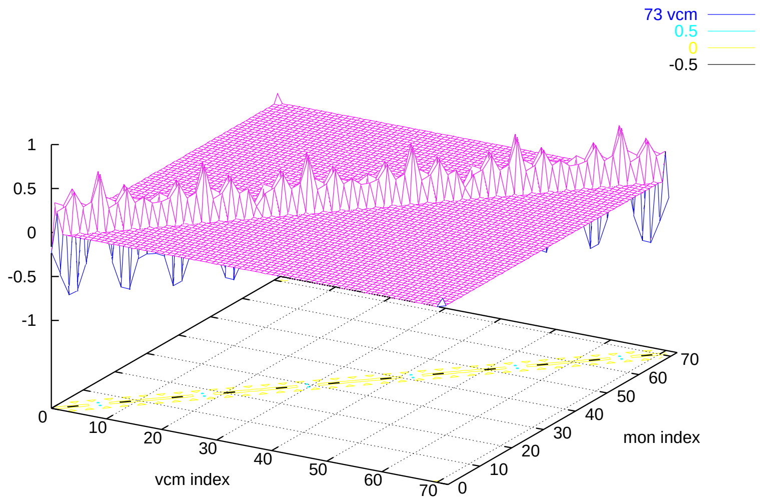
73 monitors / 36 correctors



=> Minimization of the RMS orbit (monitor averaging)

SHORT TERM STABILITY - Inverse Corrector / BPM Response Matrices (*SLS*)

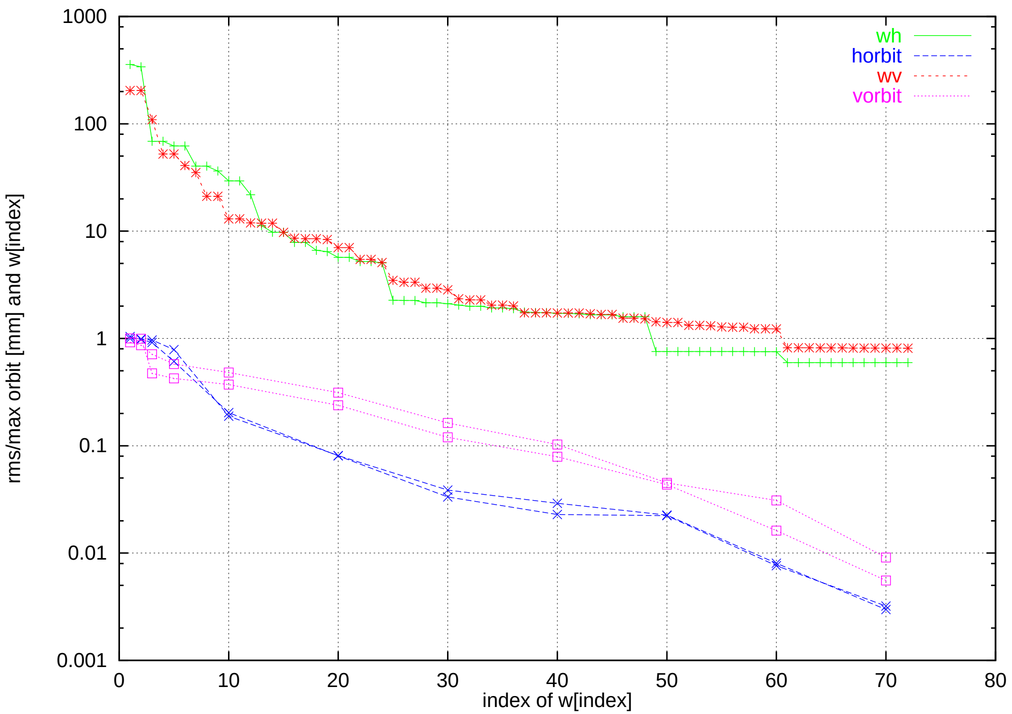




$$A_{ij}^{-1} = (V * 1/W * U^T)_{ij}$$

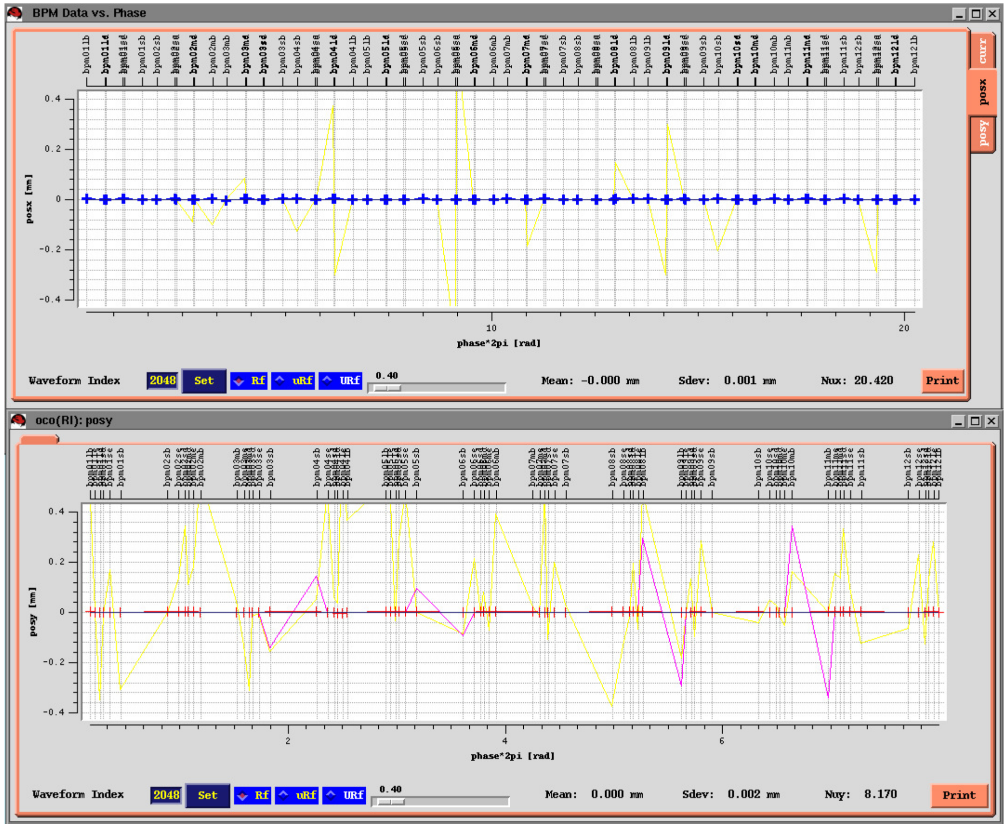
- A_{ij}^{-1} is a sparse "*tridiagonal*" matrix (3 large (+1 small) adjacent coefficients are nonzero since BPM and Corrector positions are slightly different)
  ⇒"Sliding Bump Scheme" iteratively inverts A
- A_{ij}^{-1} contains *global* information although it is a "*tridiagonal*" matrix !
  ⇒ Implementation of a Fast Orbit Feedback (FOFB)

SHORT TERM STABILITY - SVD Eigenvalues (*SLS*)



- Range of Eigenvalues $0.5 < W < 500$
- Eigenvalue Cutoff @ i_0 ($W_i = 0$ for $i > i_0$) determines the minimum achievable RMS Orbit and Corrector Strength after Correction $\Rightarrow$ “MICADO” like: the largest Eigenvalues correspond to the “Most Effective Corrector” patterns
- No Cutoff corresponds to “Matrix Inversion”. The RMS Orbit after Correction is Zero !

SHORT TERM STABILITY - Closed Orbit after Correction (*SLS*)

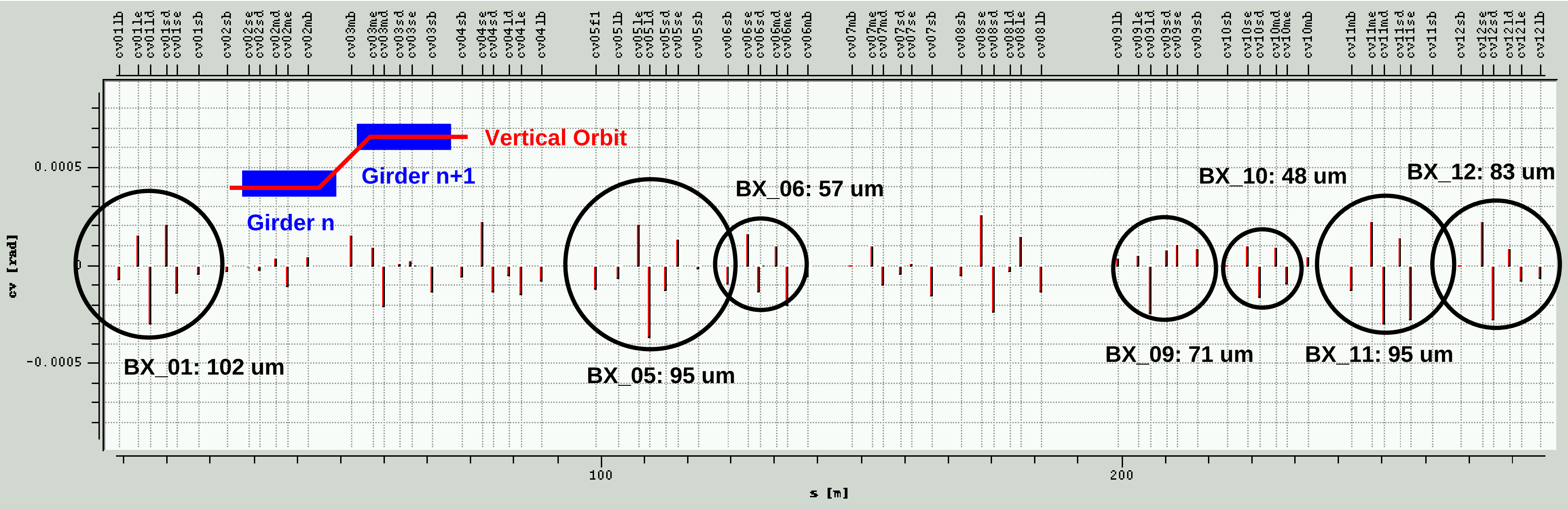


Mean: -0.000 mm Sdev: 0.001 mm Nux: 20.420

Mean: 0.000 mm Sdev: 0.002 mm Nuy: 8.170

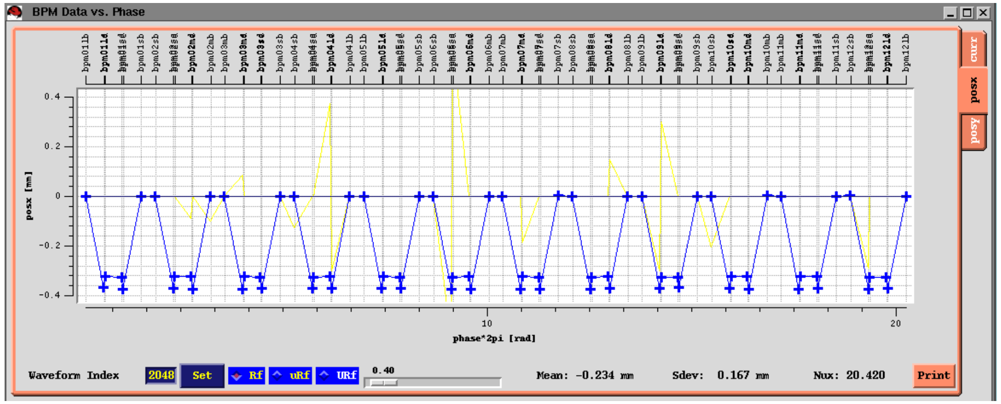
- Closed Orbit after correction deviates by $x_{rms} \approx y_{rms} \approx 1\ \mu m$ from the so-called "Golden Orbit", which contains some extra steering for the IDs (⇒No Cutoff).
- At SLS corrector values are at RMS values of $\approx$ 140 μrad (1.3 A) and $\approx$ 130 μrad (1.2 A).

SHORT TERM STABILITY - Vertical Corrector Pattern after Correction (SLS)

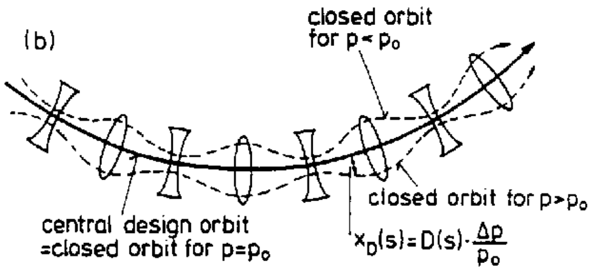


- Corrector Pattern can be used to determine alignment errors (⇒No Cutoff).
- Prominent girder-girder alignment errors related to local corrector patterns (circles).
- Girder-girder errors introduce mechanical steps driving the adjacent correctors.
- Leads to saturation of correctors in machines with large alignment errors (⇒Eigenvalue Cutoff = “Long Range Correction”).
- Without Cutoff the corrector display (corrector space) is of much more interest than the orbit display which shows mainly the residual BPM noise with respect to the “Golden Orbit” !

SHORT TERM STABILITY - How to correct Off-Energy Orbits ?



Mean: -0.234 mm Sdev: 0.167 mm Nux: 20.420



- In the case of "strong focussing" (b) the Orbit Deviation @ a location s is given by $x_0(s) = D(s)\Delta p/p_0$ with $\Delta p = p - p_0$, $D(s)$ denotes the Dispersion. $\Delta L/L_0 = \alpha_c \Delta p/p_0$ with the so-called "Momentum Compaction Factor" $\alpha_c = 1/L_0 \int_0^{L_0} D(s)/\rho(s)ds$ ($\approx\ 6 \cdot 10^{-4}$ at the SLS)
- p variations due to "Path Length" $\Delta L/L_0$ (thermal or modelling effects) changes have to be corrected by means of the RF Frequency f with $\Delta f/f = -\alpha_c \Delta p/p_0$ and NOT by the Orbit Correctors (Note: in the case of a low-α_c optics with small α_c ($\approx\ 4 \cdot 10^{-5}$ at the SLS) and large α_{c2} ($\approx\ 2 \cdot 10^{-3}$ at the SLS) the approximation $\Delta f/f = -\alpha_c \Delta p/p_0 + \alpha_{c2}(\Delta p/p_0)^2$ must be used)

⇒ Fit $\Delta p/p_0$ part of the Orbit using SVD on a 1 column response matrix containing dispersion values D_{i0} @ the BPMs and change the RF frequency by $-\Delta f$ to correct for $\Delta p/p_0$ (Note: quality of fit depends strongly on sampling of dispersion pattern (⇒sharp edges preferred))

SHORT TERM STABILITY - Orbit Correction Summary

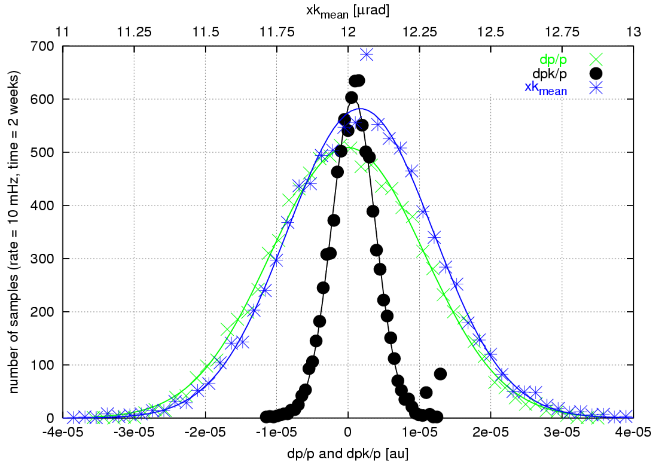
Remarks on matrix inversion:

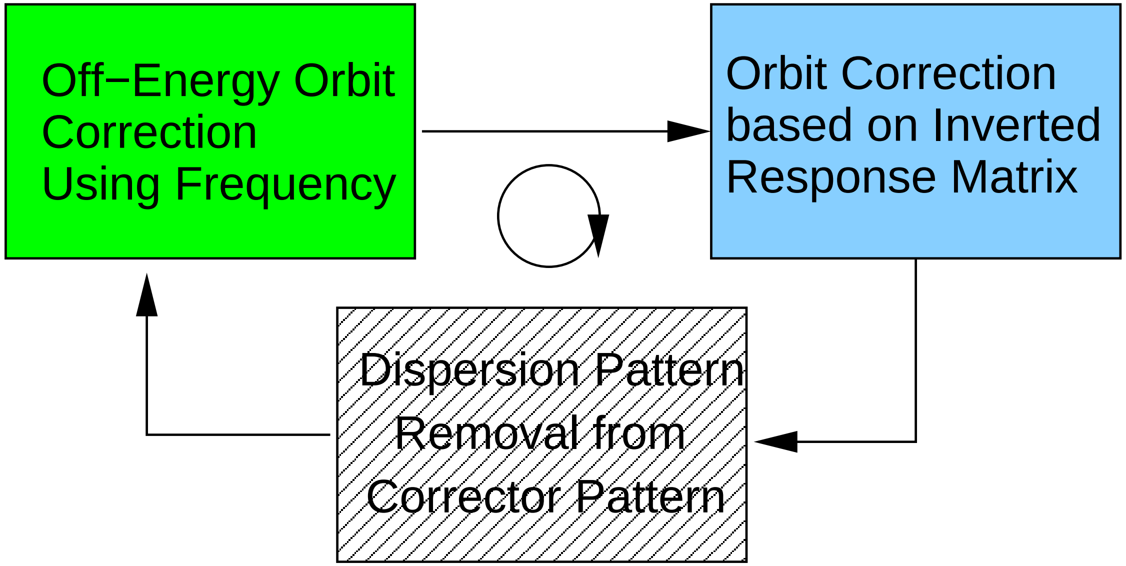
- Since modern light sources are built with very tight alignment tolerances and BPMs are well calibrated with respect to adjacent quadrupoles, orbit correction by matrix inversion in the nxn case has become an option since
  - resulting RMS corrector strength is still moderate (typically ≈100 μrad)
  - BPMs are reliable and their noise is small (no BPM averaging is performed which is similar to a local feedback scenario)
- This allows to establish any desired "golden orbit" within the limitations of the available corrector strength and the residual corrector/BPM noise (⇒golden orbit "equalizer" with one slider/BPM)

Remarks on horizontal orbit correction:

- Dispersion orbits due to "path length" changes (circumference, model-machine differences, rf frequency) need to be corrected by means of the rf frequency f.
- A gradual build-up of a dispersion D related corrector pattern $\sum A_{ji}^{-1} D_i$ with a nonzero mean must be avoided ⇒ leads together with rf frequency change to a corrected orbit at a different beam energy.
- Subtract pattern $\sum A_{ji}^{-1} D_i$ from the actual corrector settings before orbit correction in order to remove ambiguity (orbit correction "does not care" about the initial corrector pattern !)

SHORT TERM STABILITY - Orbit Correction Loop





Off−Energy Orbit Correction Using Frequency

Orbit Correction based on Inverted Response Matrix

Dispersion Pattern Removal from Corrector Pattern

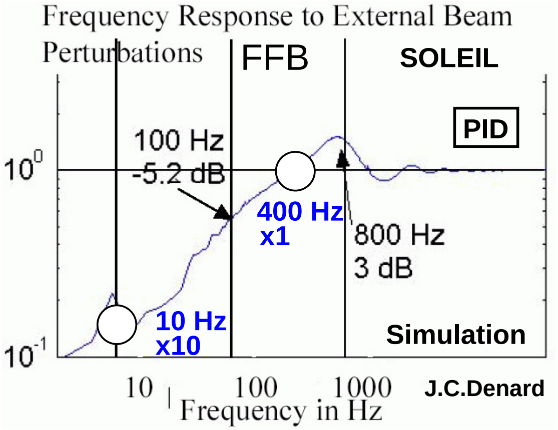
SHORT TERM STABILITY - Feedback Implementation I

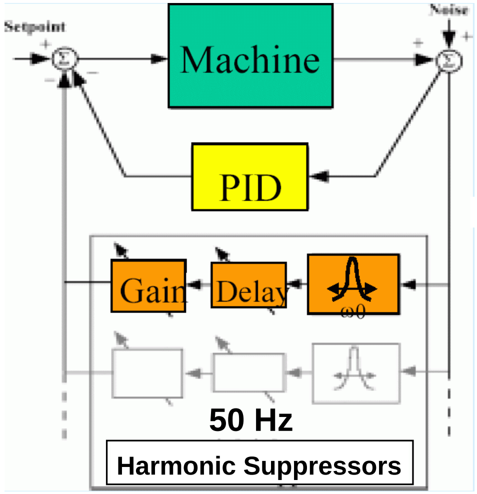
In order to implement a global orbit feedback based on the described algorithm which stabilizes the electron beam with respect to the established “Golden Orbit” up to frequencies ≈100 Hz with sub-micron in-loop stability the following is needed:

- BPM data acquisition rates of at least ≈1-2 kHz.
- Integrated BPM noise must not exceed a few hundred nanometers (achieved with modern digital four channel (parallel) and analog multiplexed systems).
- A fast network for BPM data distribution around the ring or a central point since every Corrector j in general depends on all BPM i readings.
- Since matrix multiplications with the BPM i vector can be parallelized a distribution on several CPU units handling groups of Corrector j is a natural solution.
- “Inverted” matrix can be sparse depending on the BPM/Corrector layout such that most of the off-diagonal coefficients are zero ⇒ only subset of all BPM readings in the vicinity of the individual correctors determines their correction values.
  At the SLS 73 BPMs with adjacent Correctors in both planes, phase advance between Correctors $<180^\circ$ ⇒ *inverted 73x73 matrix “resembles” a correction with interleaved closed orbit bumps made up from 3 successive Correctors (“Sliding Bump Scheme”).*

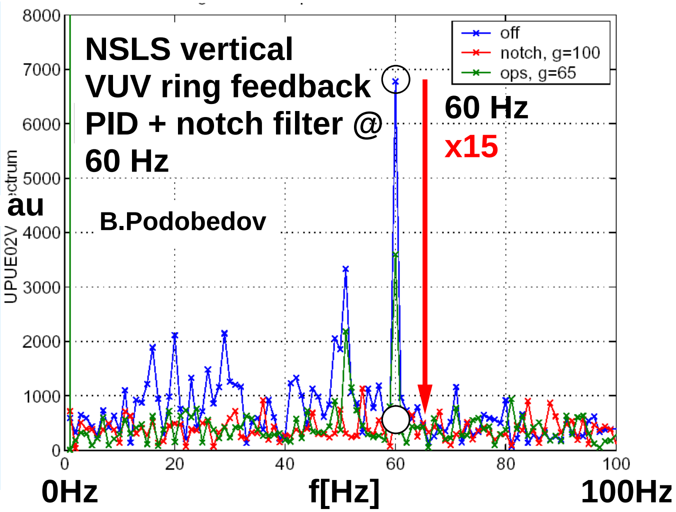
SHORT TERM STABILITY - Feedback Implementation II - Loop

- Feedback loop closed with PID controller function optimizing **gain, bandwidth and stability** of the loop.
- **Notch filters** allow to add additional “**harmonic suppression**” (D. Bulfone) of particularly strong lines at 50/60 Hz.

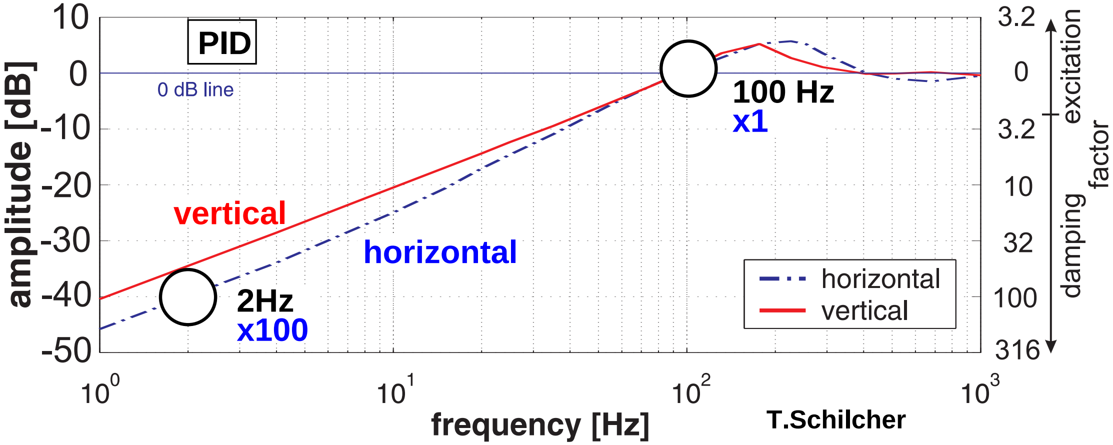




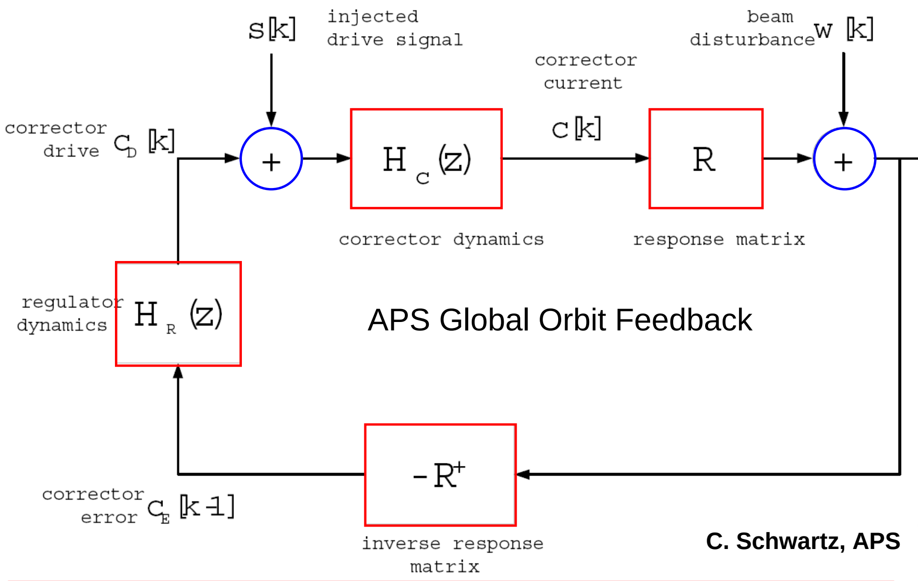
ELETTRA **D. Bulfone**



Closed loop transfer functions at the SLS (damping up to ~100 Hz)

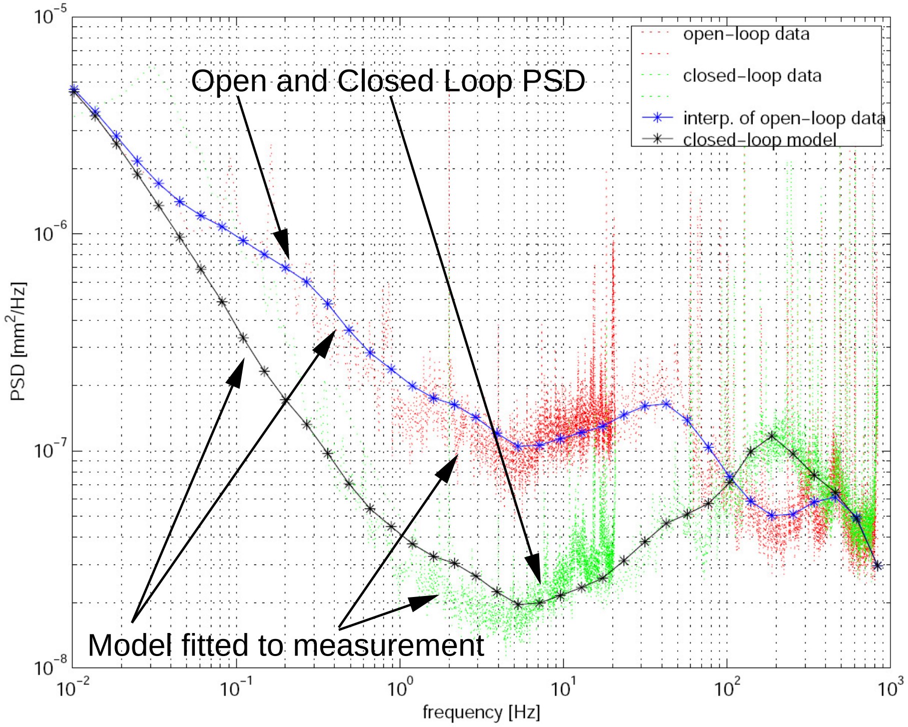


SHORT TERM STABILITY - Feedback Implementation III - Loop Simulation



APS Global Orbit Feedback

C. Schwartz, APS

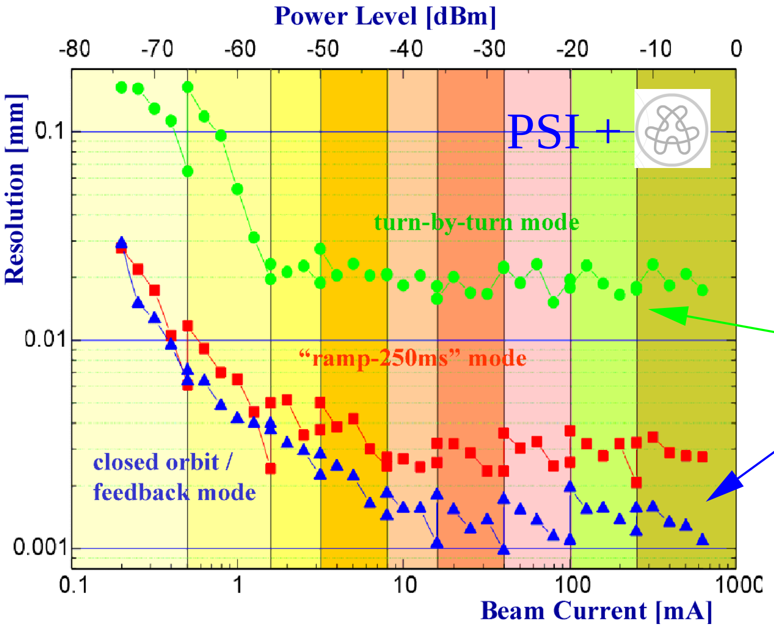


Simulation of the Fast Orbit Feedback loop at APS gives good agreement with measurements of open and closed loop PSDs.

Helps to derive specifications for the various components of a feedback in the design phase.

Allows to change feedback parameters in simulation without touching the running feedback.

SHORT TERM STABILITY - Feedback Implementation IV - BPM System (*SLS*)



Only One BPM System in Different Operation Mode for All Machines

Turn−by−Turn:

1 MSample/s, <20 μm

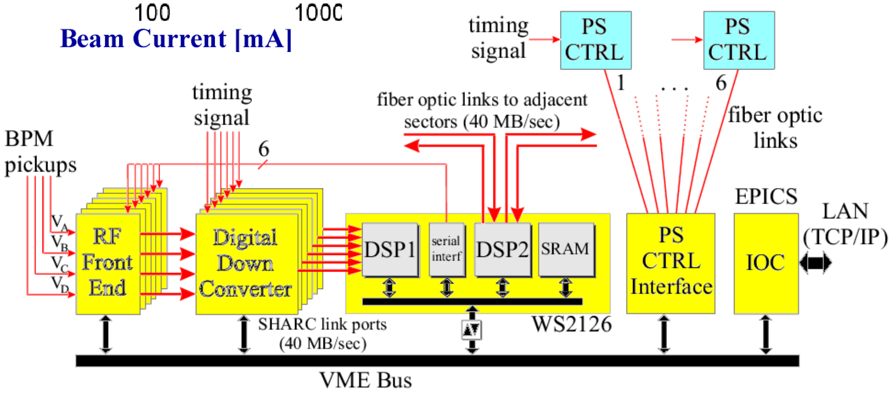
Closed Orbit:

4 KSample/s, <0.8 μm

~300 nm <100 Hz

Turn−by−Turn:

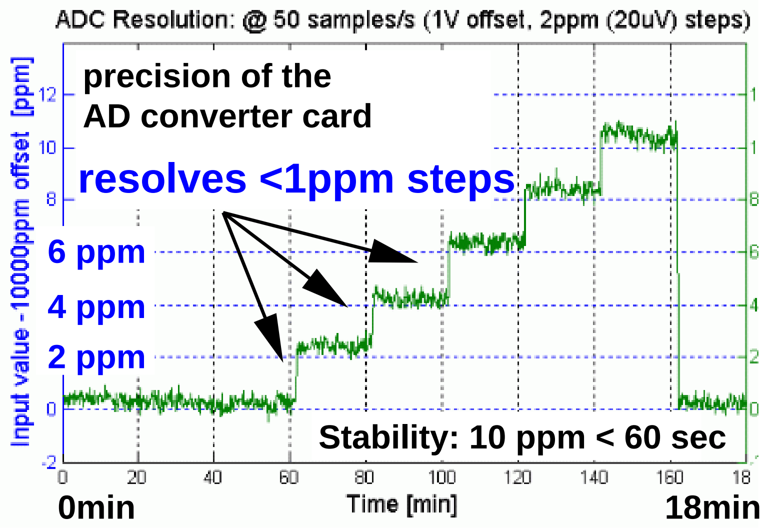
Vital for Commissioning

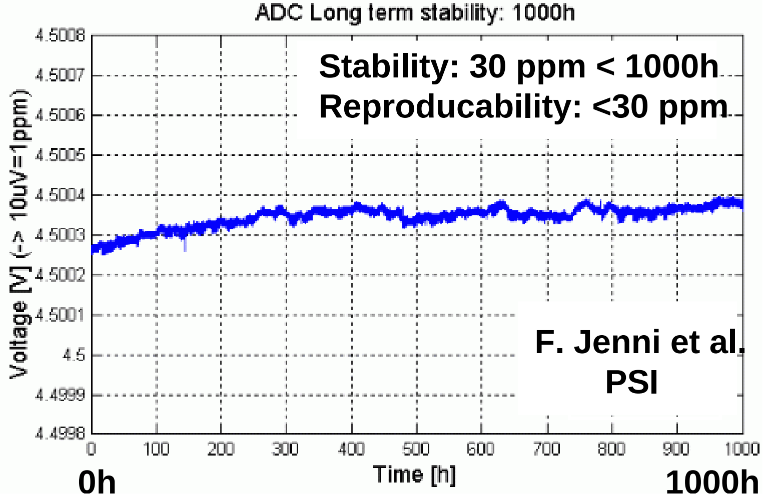


Closed Orbit Mode −> Fast Orbit Feedback

SHORT TERM STABILITY - Feedback Implementation V - Power Supplies (PS)

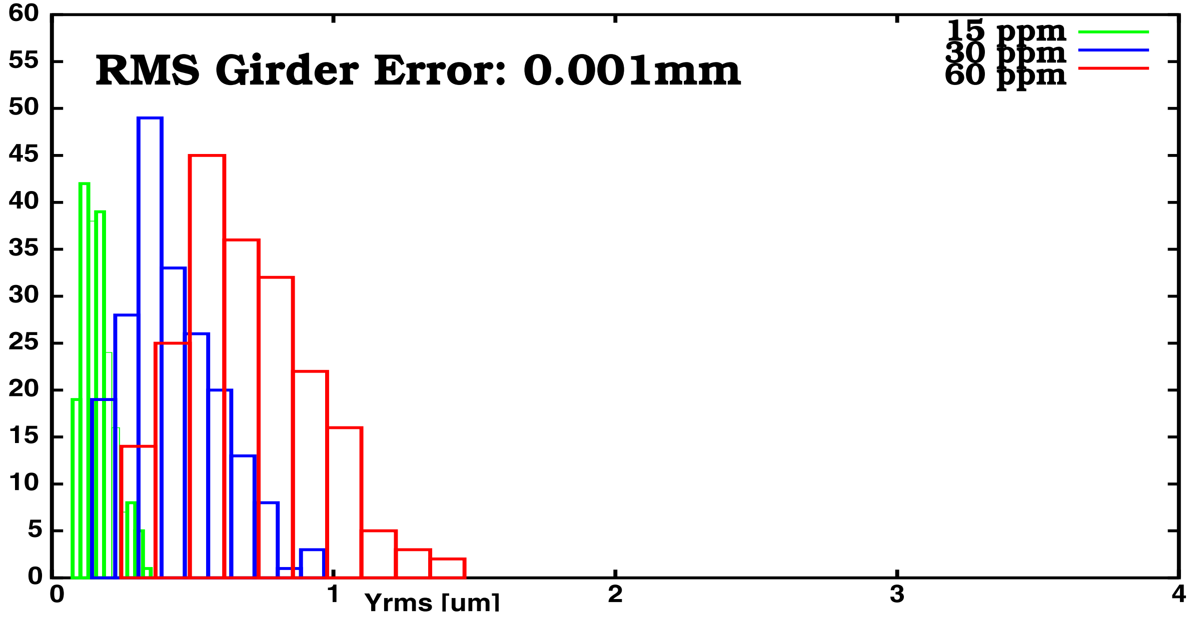
- Minimum correction strength defined by power supply (PS) resolution for a strength range Δk must be within the BPM noise: **typically ≈10 nrad ⇒ ≈18 bit (≈4 ppm) resolution for a PS with Δk ±1 mrad**.
- **PS with digital control** have reached noise figures of **<1 ppm providing kHz small-signal bandwidth** ⇒ possibility to use the same correctors for DC and fast correction (⇒ SLS).
- Eddy currents induced in the vacuum chamber should not significantly attenuate or change the phase of the effective corrector field up to the data acquisition rate.
- Eddy currents are proportional to the thickness and electrical conductivity of materials ⇒ **thin laminations (≤1 mm thickness)** or **air coils** (⇒ **SOLEIL**) should be used.
- Low conductive materials preferred for vacuum chambers. Eddy currents in vacuum chambers impose the most critical bandwidth limitation on the feedback loop.





SHORT TERM STABILITY - Feedback Implementation VI - PS Resolution (*SLS*)

Optics Code TRACY estimates Residual Vertical RMS Orbit after Orbit Correction as seen by the BPMs (histograms for 200 seeds introducing RMS girder misalignment of 1μm) for the SLS:

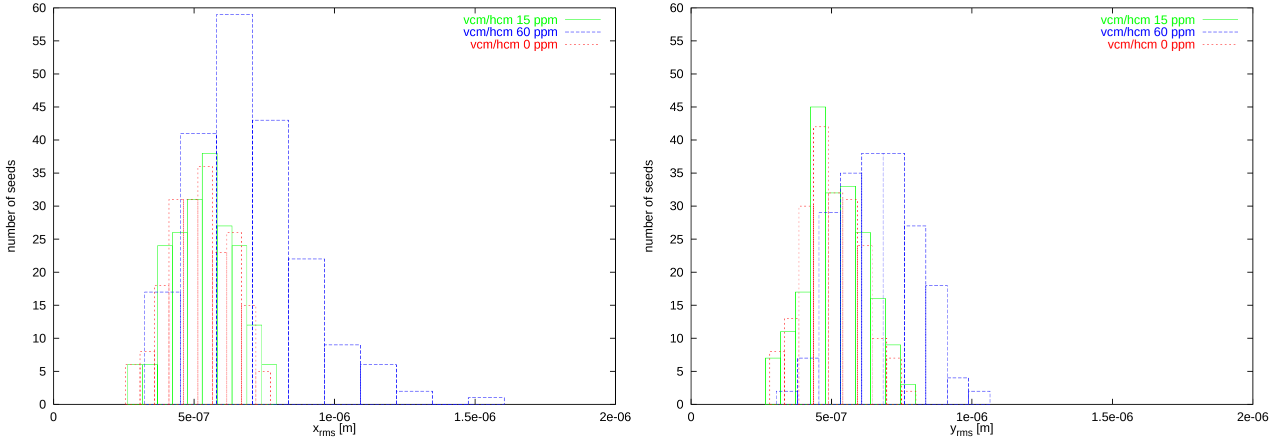


- 1 ppm in amplitude corresponds to a resolution of 10^{-6} at a maximum Current of 7 A ($\approx$ 860 μrad in the vertical plane)
- 60 ppm: y_{rms} = 0.75μm, 30 ppm: y_{rms} = 0.5μm, 15 ppm: y_{rms} = 0.25μm

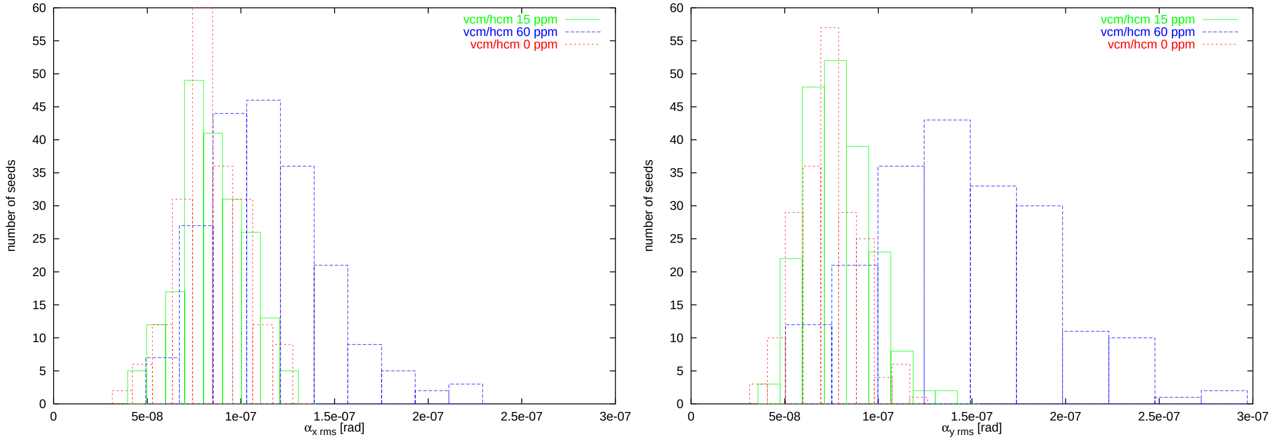
$\Rightarrow$ 15 ppm ($\approx$ 10 nrad or 100 μA) sufficient

SHORT TERM STABILITY - Feedback Implementation VII - Orbit @ IDs (SLS)

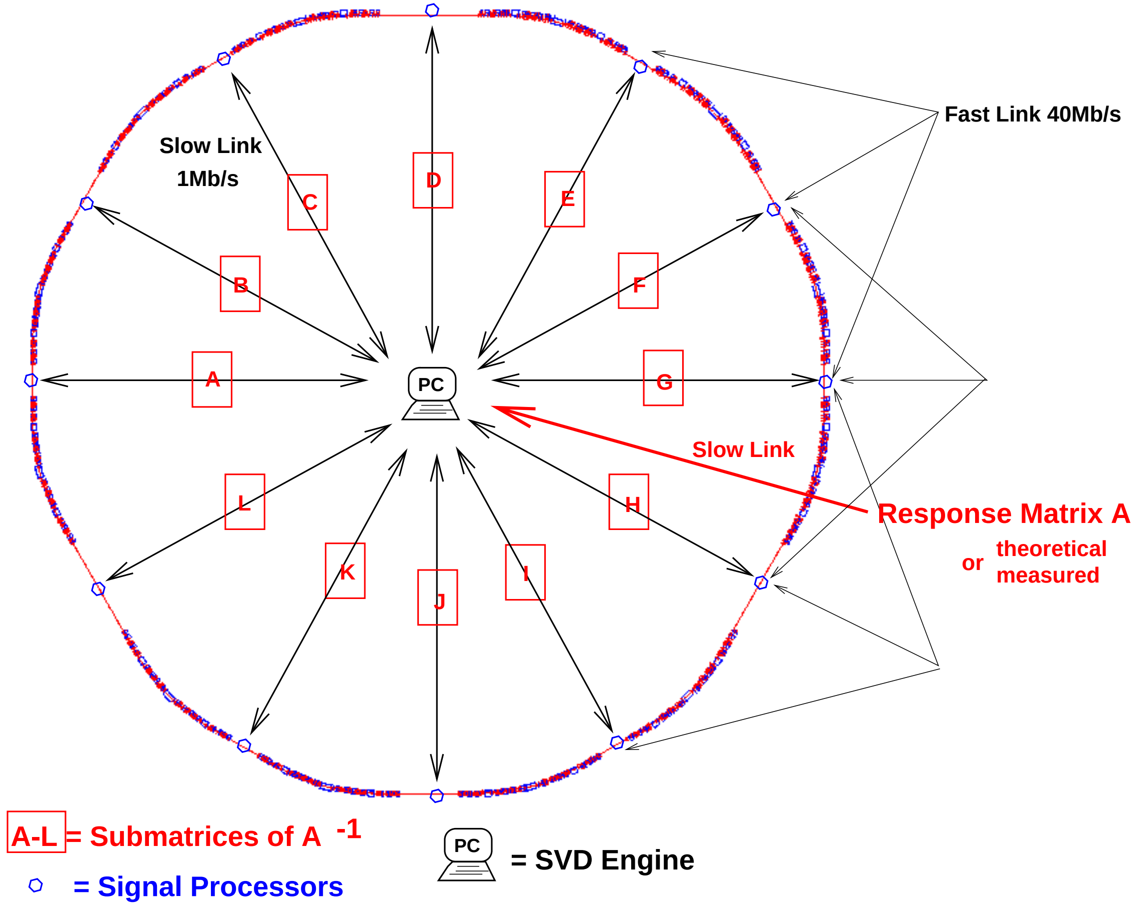
RMS Position @ Insertion Devices with $\beta_x \approx 1.4$m,$\beta_y \approx 0.9$m (x/y_{rms}= 0.5μm for 15 ppm):



RMS Angle at the Insertion Devices ($\alpha_{x/yrms}$= 0.08μrad for 15 ppm):

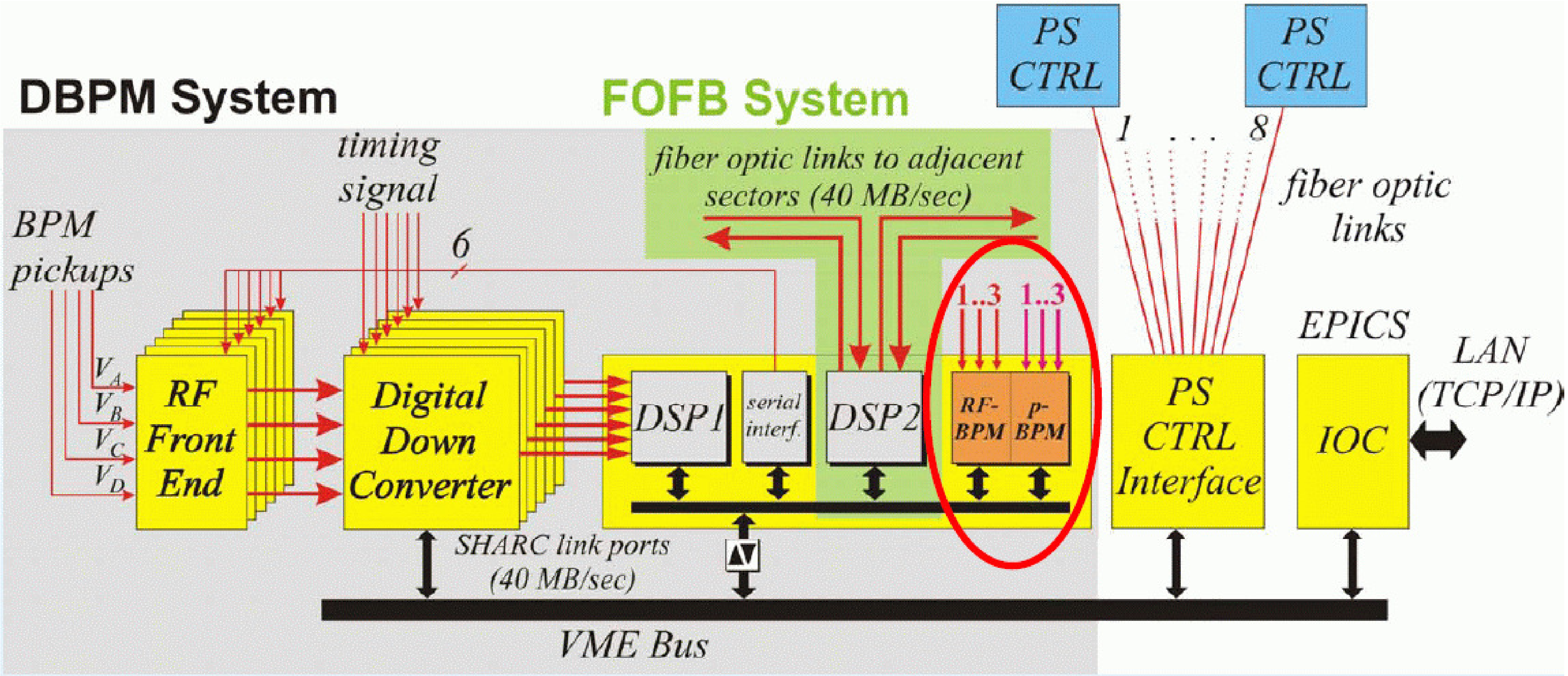


SHORT TERM STABILITY - Feedback Implementation VIII - Scheme (*SLS*)



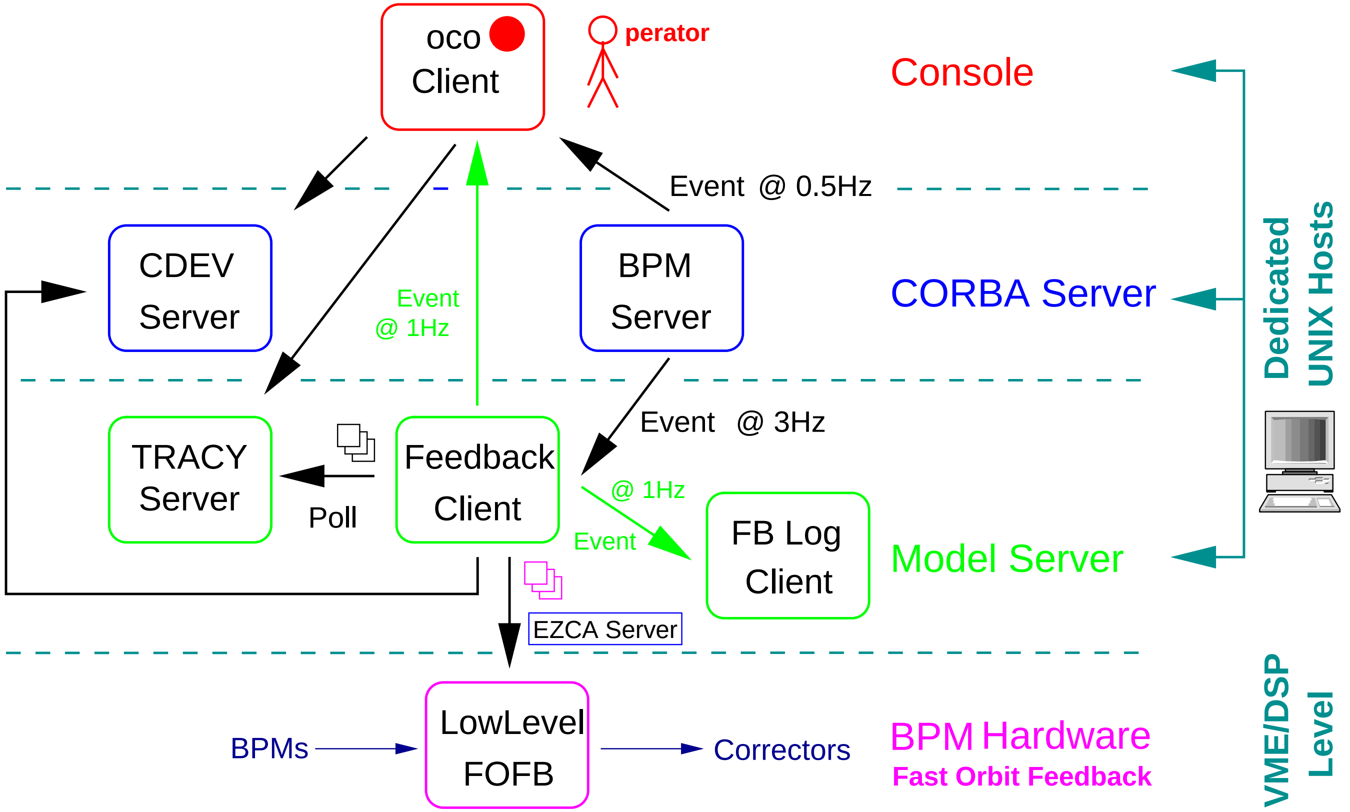
- Dedicated Signal Processors perform Matrix Multiplications in parallel !

SHORT TERM STABILITY - Feedback Implementation IX - HW Layout (*SLS*)



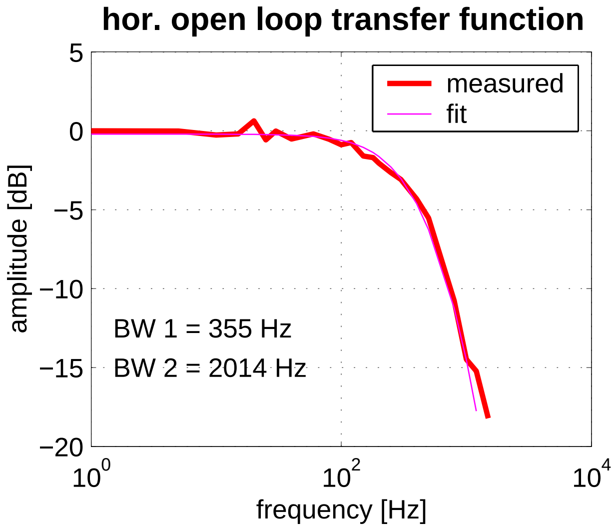
- integration of photon BPMs into FOFB (→IR beamlines)
- DSP processor: ADSP2106x (on the market since Sep. 1994)
- DDC: Intersil HSP50214 (on the market since ~1997)

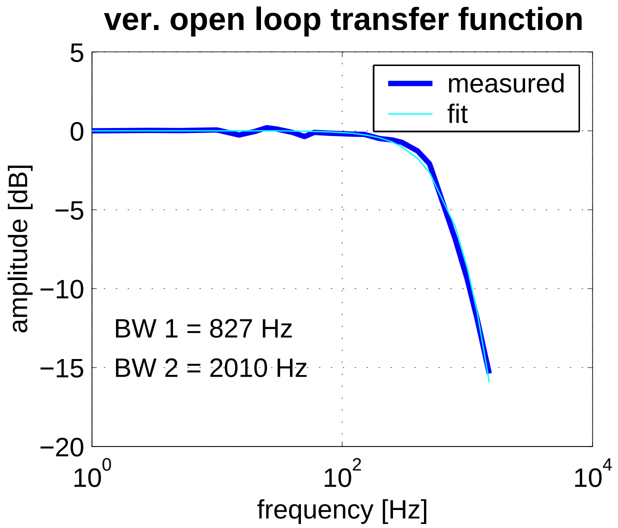
SHORT TERM STABILITY - Feedback Implementation X - Software (*SLS*)

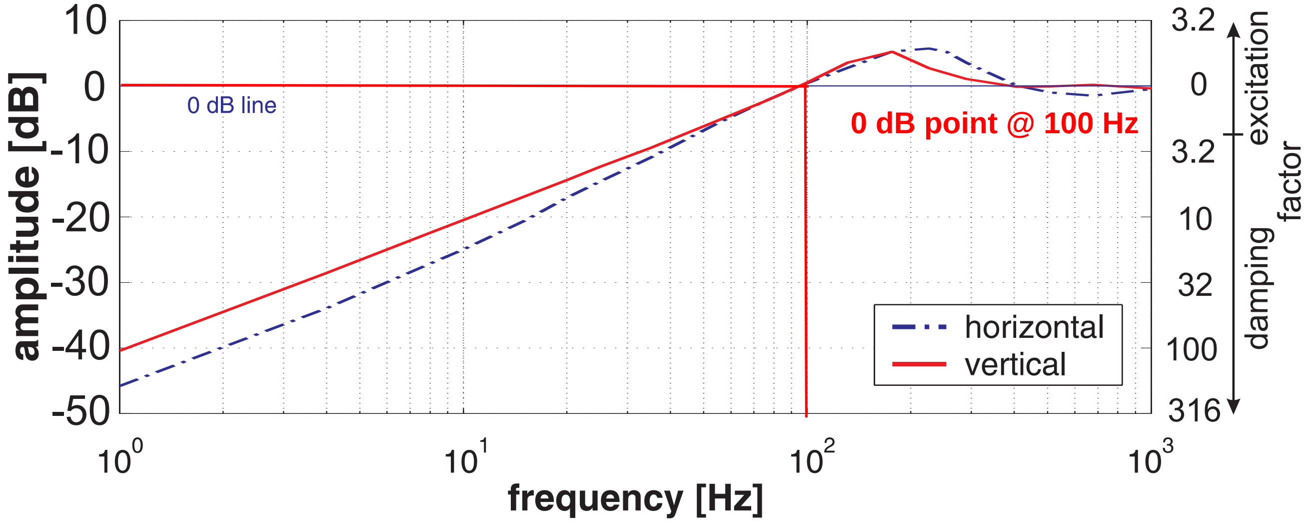


- Development within a Client-Server (Common Object Request Broker CORBA) environment
- Hard Correction ("Matrix Inversion" on the Model based Response Matrix using SVD)
- BPM Datasets @ 3 Hz, average over 3 successive Datasets => ≈ 1 Hz correction rate (toggle between x/y plane => 2 s for full cycle)

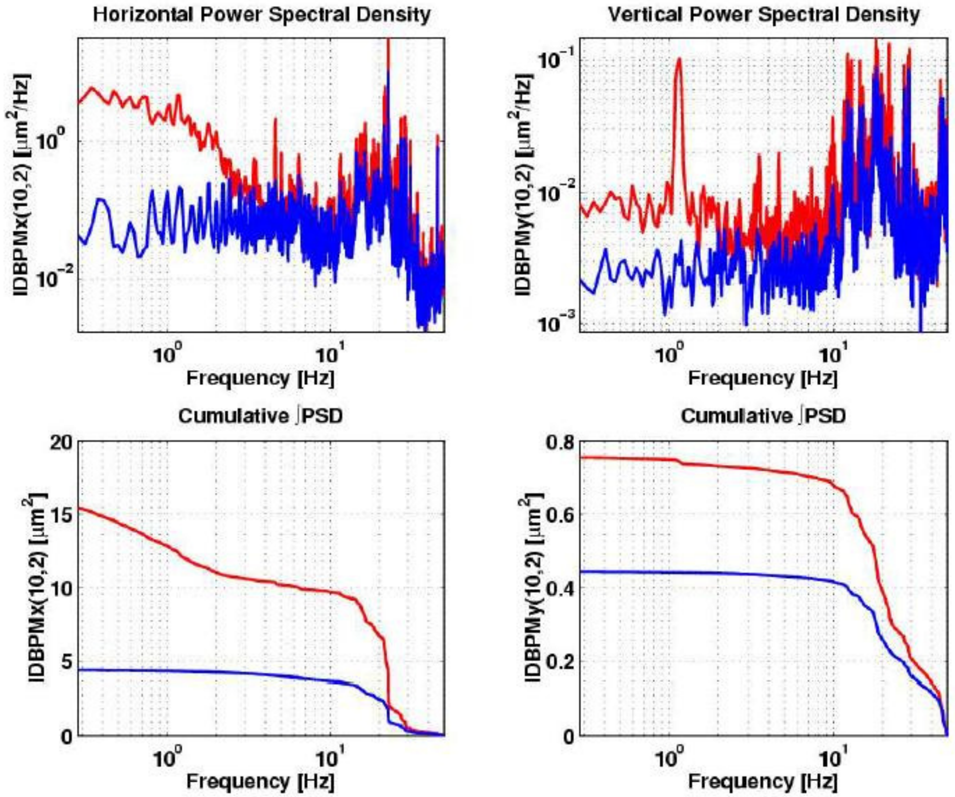
SHORT TERM STABILITY - Open/Closed Loop Transfer Functions (*SLS*)

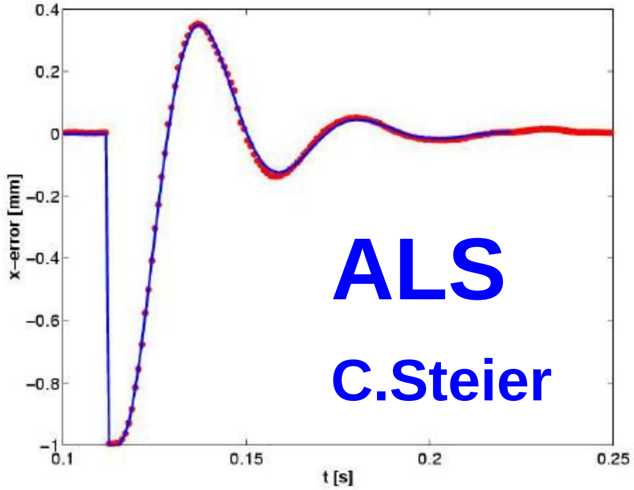






SHORT TERM STABILITY - ALS





ALS

C.Steier

- Combination of fast and slow global orbit feedbacks in both planes – no frequency deadband
- Fast Feedback currently 24 BPMs in each plane and 22 correctors in each plane. 1.11 kHz update rate, bandwidth DC-40 Hz.
- Slow Feedback 52 BPMs in each plane, 26 horizontal correctors, 50 vertical correctors, RF frequency correction. 1 Hz update rate, about 60% single step gain, bandwidth DC-0.1 Hz.
- Slow feedback communicates with fast feedback to avoid interference in frequency overlap range. Setpoints/golden orbit used by fast feedback is updated at rate of slow feedback.

- Beam motion with feedback in open (red) and closed loop (blue).
- Feedback is quite effective up to about 40 Hz
- Correction at low frequencies down to the BPM noise floor (noise floor is not subtracted in above plots).

Global Feedback

1.1 KHz DC–40Hz

SHORT TERM STABILITY - Feedbacks at LS Worldwide

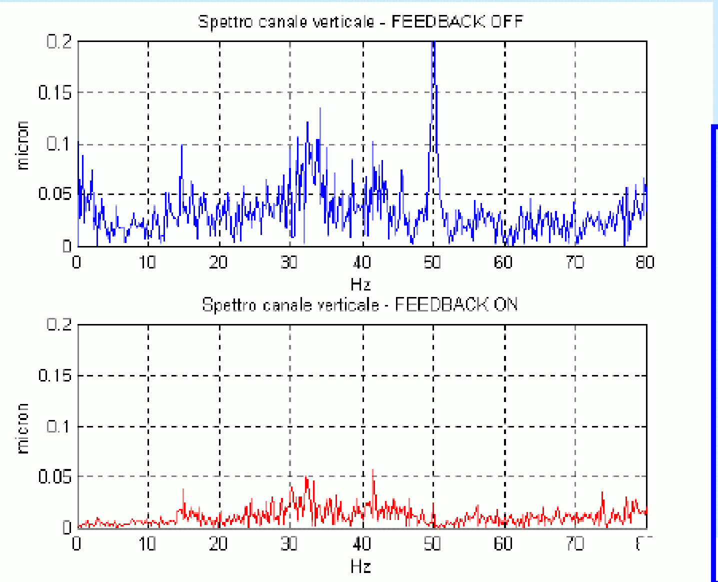
SR Facility	**BPM Type**	**max. BW**	**Stability**
ALS	RF-BPMs	$<$50 Hz	$<$**1** μ**m**
APS	RF&X-BPMs	50 Hz	$<$**1** μ**m**
ESRF	RF-BPMs	100 Hz	$<$**0.6** μ**m**
NSLS	RF&X-BPMs	$<$200 Hz	**1.5** μ**m**
SLS	RF&X-BPMs	100 Hz	$<$**0.3** μ**m**
DIAMOND	RF-BPMs	150 Hz	**0.2** μ**m**
SOLEIL	RF-BPMs	150 Hz	**0.2** μ**m**
SPEAR3	RF-BPMs	100 Hz	$<$**3** μ**m**
ELETTRA	RF-BPMs	100 Hz	**0.2** μ**m**
Super-ACO	RF-BPMs	$<$150 Hz	$<$**5** μ**m**
BESSY	RF-BPMs	$<$100 Hz	$<$**1** μ**m**
DELTA	RF-BPMs	$<$150 Hz	$<$**2** μ**m**
SPring-8	RF-BPMs	100 Hz	$<$**1** μ**m**
APS	X-BPMs	50 Hz	$<$**1** μ**m**
BESSY	X-BPMs	50 Hz	$<$**1** μ**m**

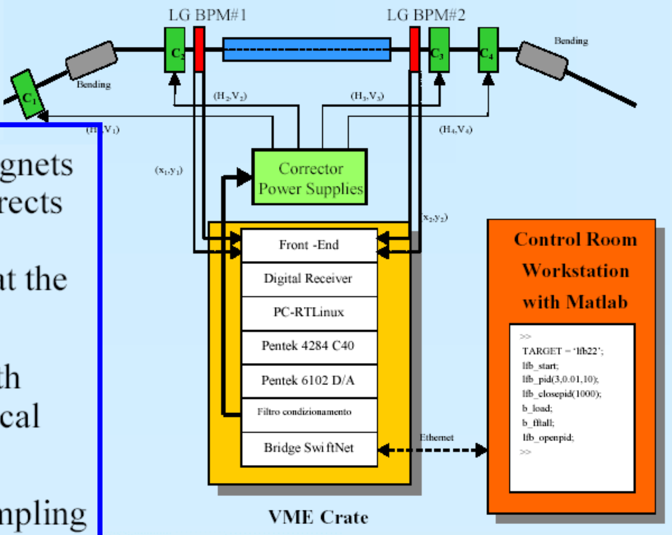
Compilation of
operational global,
retired global,
proposed global
operational local
fast orbit feedbacks at light sources world-wide *updated version V.Schlott, EPAC'02*
Not in list:
PETRA-3 NSLS-II TPS ...

SHORT TERM STABILITY - Local Feedbacks

- Local fast orbit feedbacks stabilize orbit position and angle at ID centers locally without effecting the orbit elsewhere by a superposition of symmetric and asymmetric closed orbit bumps consisting of ≥ 4 correctors per plane around the ID.
- Photon BPMs (X-BPMs) which are located in the beam line frontends measuring photon beam positions provide very precise information about orbit fluctuations at the ID source point at a typical bandwidth of $\approx$2 kHz. *With two X-BPMs position and angle fluctuations can be disentangled. Unfortunately the reading depends on the photon beam profile and thus on the individual ID settings*.
  - APS is operating X-BPM based feedbacks on their dipole and ID X-BPMs at fixed gap.
  - BESSY has the prototype for an X-BPM based feedback on an APPLE II ID.
  - ELETTRA implemented a feedback for an electromagnetic elliptical wiggler (EEW) based on a new type of digital “low gap” BPM (recently commissioned global fast orbit feedback).
- **If several global and/or local feedbacks are operated they need to be decoupled**. Either they are well separated in frequency which evidently leads to **correction dead bands** (APS) **or** they run in a **cascaded master-slave configuration** (SLC,APS,ALS,SLS).

SHORT TERM STABILITY - *ELETTRA*





```
>>
TARGET = 'lfb22';
lfb_start;
lfb_pid(3,0.01,10);
lfb_closepid(1000);
b_load;
b_fftall;
lfb_openpid;
>>
```

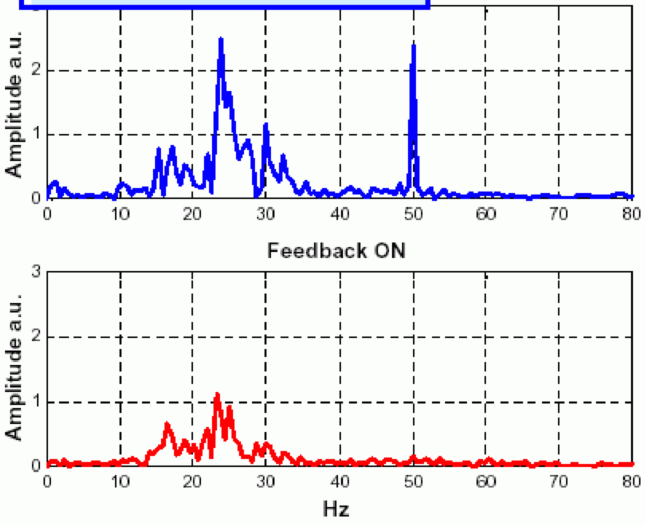
- Four corrector magnets local bump that corrects the electron beam position and angle at the ID centre
- Closed loop in both horizontal and vertical planes
- Beam position sampling rate = 8kHz

- Beam position spectra at low-gap BPM #1 with local feedback off/on. The rms of the position signal in the 0-80 Hz range is reduced from 1.24 μm to 0.2 μm.

Fast Local Feedback

@ EEW (Electromagnetic Elliptical Wiggler)

D. Bulfone



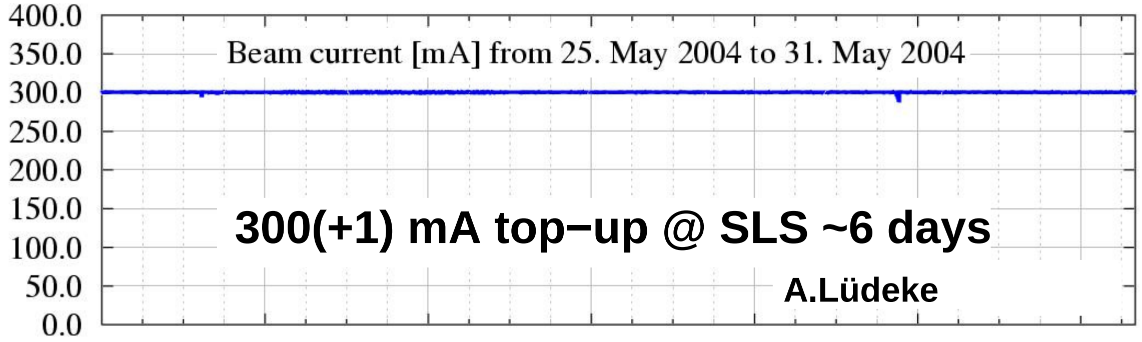
- Beam position spectra at photon-BPM along the corresponding beam-line

tal BPMs at ELETTRA

MEDIUM TERM STABILITY

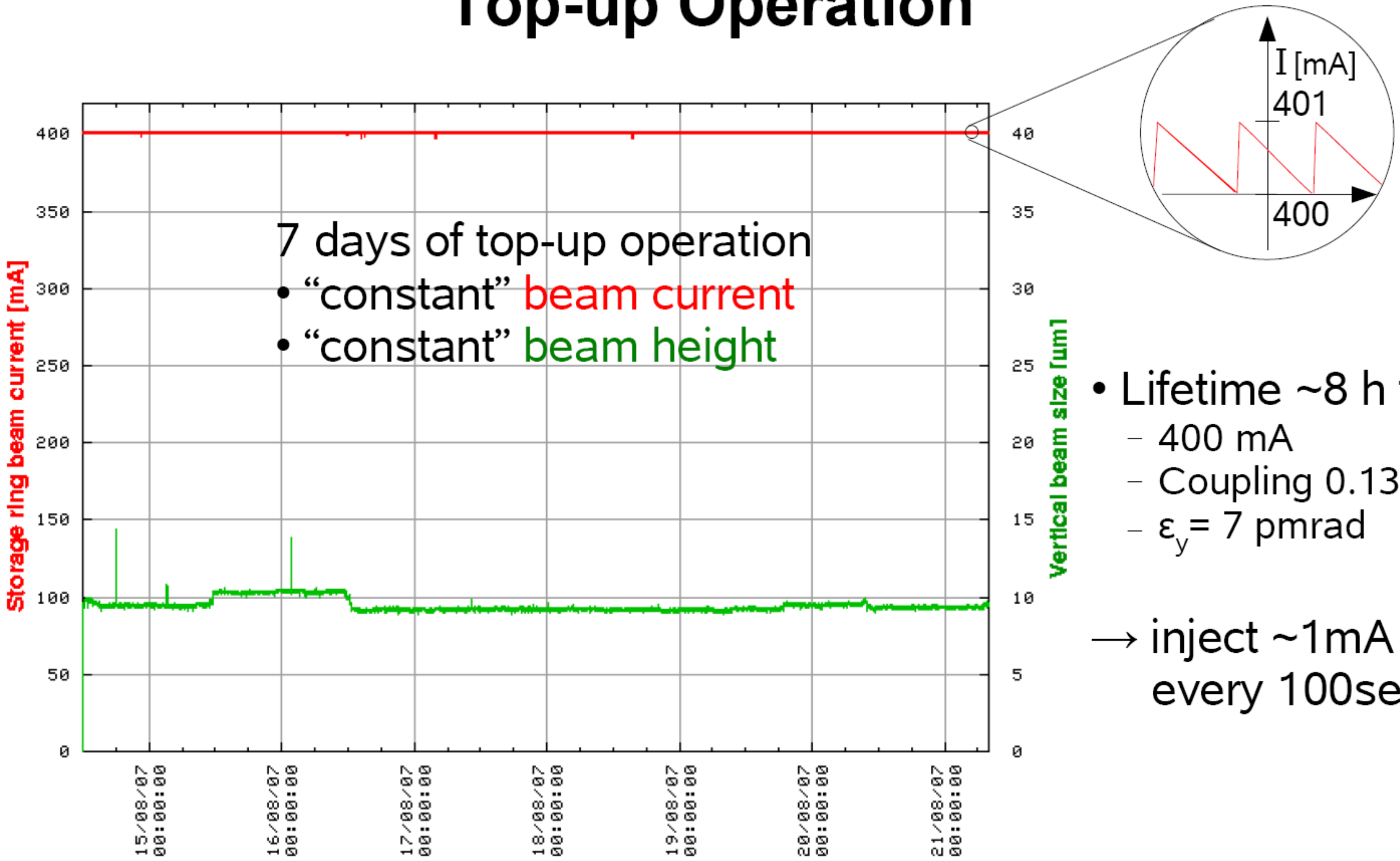
In this regime high mechanical stability is needed to achieve stability on the sub-micron level:

- Stabilization of tunnel, cooling water temperature and digital BPM electronics (T. Schilcher) to $\approx \pm 0.1°$ and the experimental hall to $\approx \pm 1.0°$.
- Minimization of thermal gradients by discrete photon absorbers and water-cooled vacuum chambers.
- Mechanical decoupling of BPMs with bellows, stiff BPM supports with low temperature coefficients (Invar (SPEAR3, SOLEIL), Carbon Fiber (ELETTRA) and/or monitoring of BPM positions (ELETTRA, SOLEIL, DIAMOND, SLS).
- Monitoring of girder positions (Hydrostatic Leveling System, Horizontal Positioning System (SLS)).
- Full energy injection and stabilization of the beam current to ≈0.1 % (“top-up” operation):



MEDIUM TERM STABILITY - Top-up I *(SLS)*

Top-up Operation



7 days of top-up operation

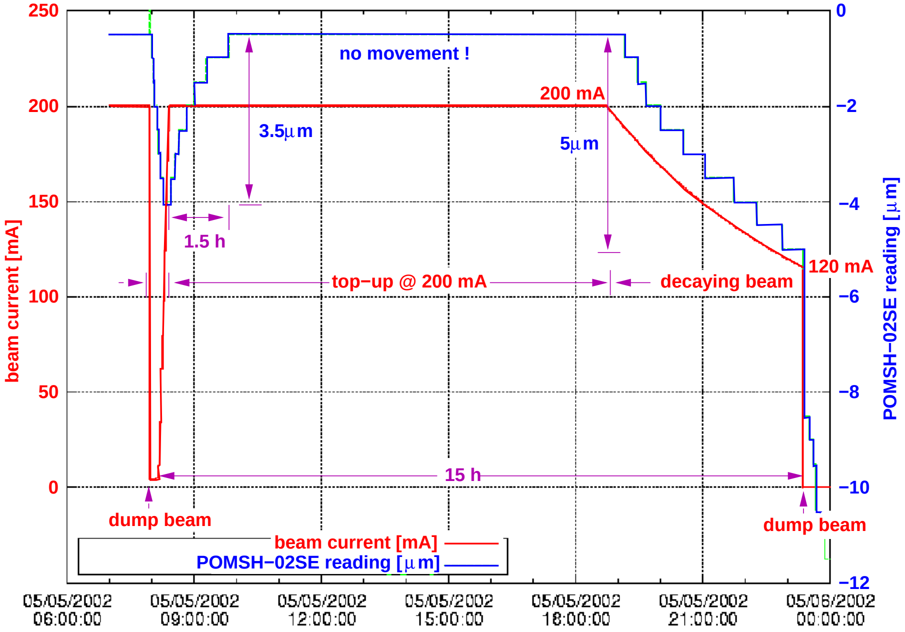
- “constant” beam current
- “constant” beam height

- Lifetime ~8 h for:
  - 400 mA
  - Coupling 0.13 %
  - ε_y= 7 pmrad

→ inject ~1mA every 100sec

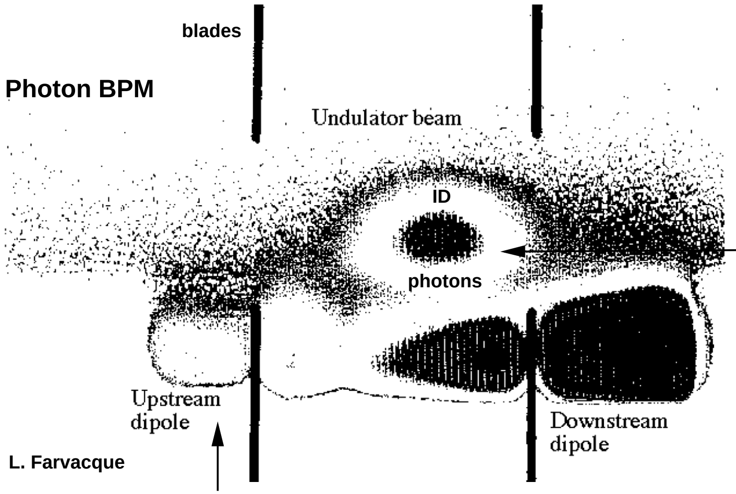
MEDIUM TERM STABILITY - Top-up II

- “Top-up” operation guarantees a constant electron beam current and thus a constant heat load on all accelerator components. It also removes the current dependence of BPM readings under the condition that the bunch pattern is kept constant (B. Kalantari)
- Horizontal mechanical offset (≈0.5 μm resolution) of a BPM located in an arc of the SLS storage ring with respect to the adjacent quadrupole in the case of beam accumulation,“top-up” @ 200 mA and decaying beam operation at 2.4 GeV:
  - Accumulation and decaying beam operation: BPM movements of up to 5 μm.
  - “Top-up” operation: no BPM movement during “top-up” operation at 200 mA after the thermal equilibrium is reached (≈1.5 h).



- APS (1 %), SLS (0.3 %), (A. Lüdeke, SPring-8 (0.1 %) (H. Tanaka) are running “top-up” in user operation.
- ALS (D. Robin) just got the permission.
- DIAMOND, SOLEIL prepare for “top-up”.

MEDIUM TERM STABILITY - Orbits in a Different Light - X-BPMs

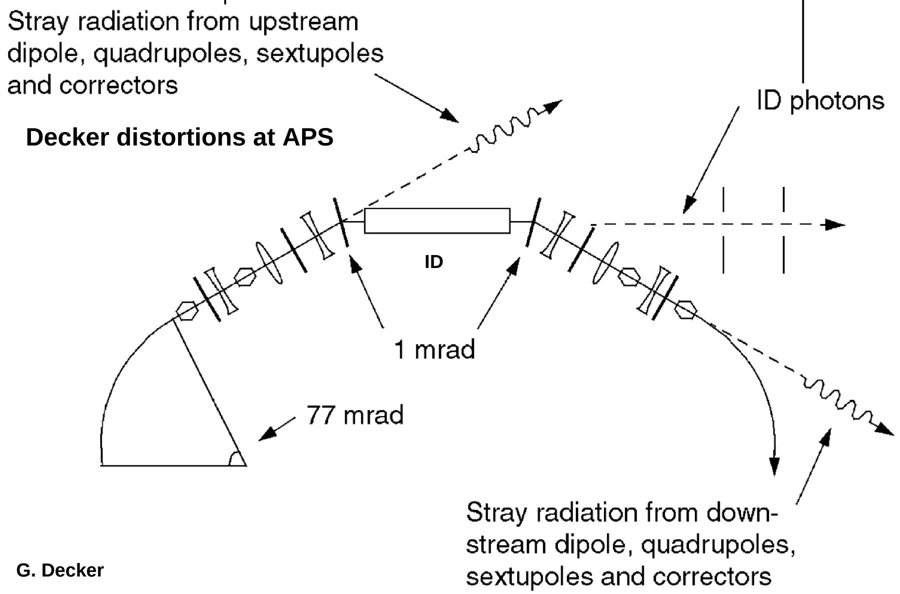


L. Farvacque

stray radiation from up− and down−stream magnets bias the reading of a Photon BPM

Solution

change strength of up− and down−stream dipoles (APS: 78−>77 mrad) add 2 extra magnets (APS: 1 mrad) to account for the difference.

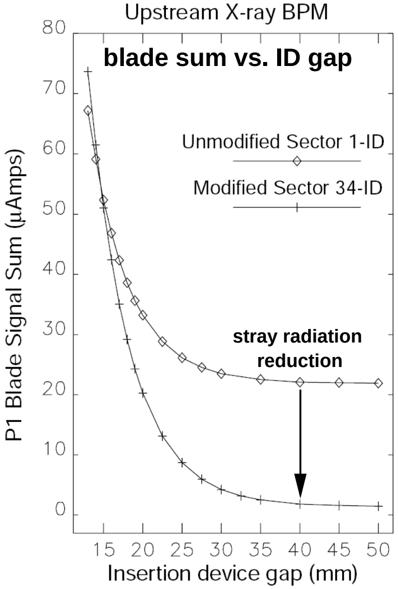


Stray radiation from upstream dipole, quadrupoles, sextupoles and correctors

Decker distortions at APS

Stray radiation from downstream dipole, quadrupoles, sextupoles and correctors

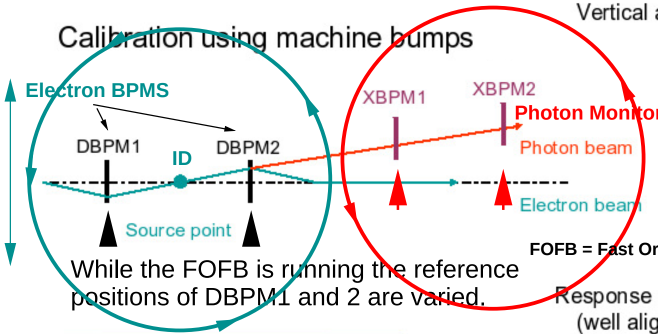
G. Decker



MEDIUM TERM STABILITY - Calibration of an X-BPM (*SLS*)

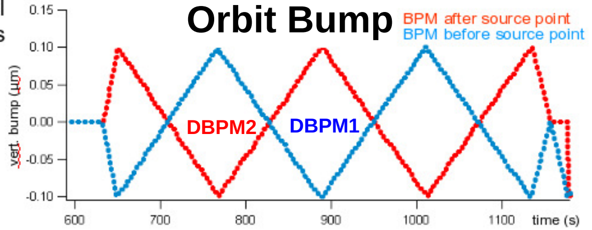
Change the references of DBPM1/2 → stabilize XBPM1/2

Vertical asymmetrical bumps



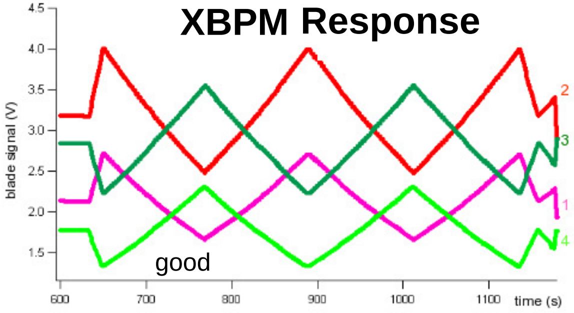
While the FOFB is running the reference positions of DBPM1 and 2 are varied.

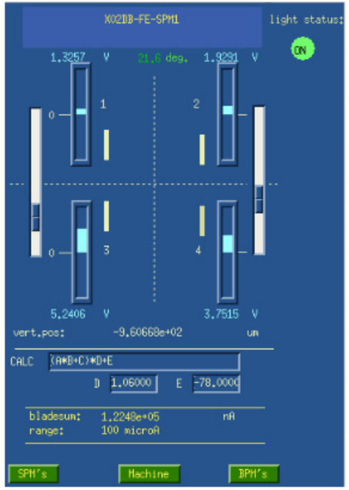
FOFB = Fast Orbit Feedback



+−100 um bump amplitude

Response of the blades (well aligned monitor)





1.3257 V 21.6 deg. 1.9291 V

5.2406 V 3.7515 V

vert.pos: -9.60668e+02 um

CALC (A*B+C)*D+E

D 1.06000 E -78.0000

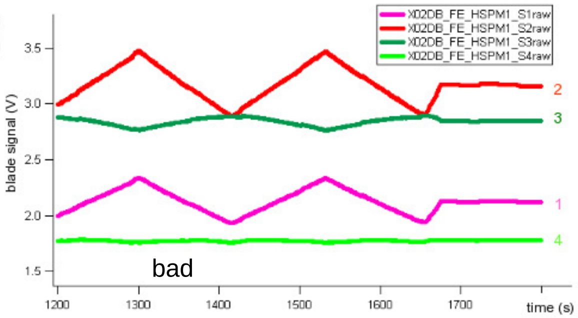
bladesum: 1.2248e+05 nA

range: 100 microA

Synoptic view of the **XBPM** in the control system

XBPM1+2 can measure position and angle of the electron beam at the center of the insertion device (ID) !

Response of the blades (badly aligned monitor)



Courtesy: Elsa van Garderen

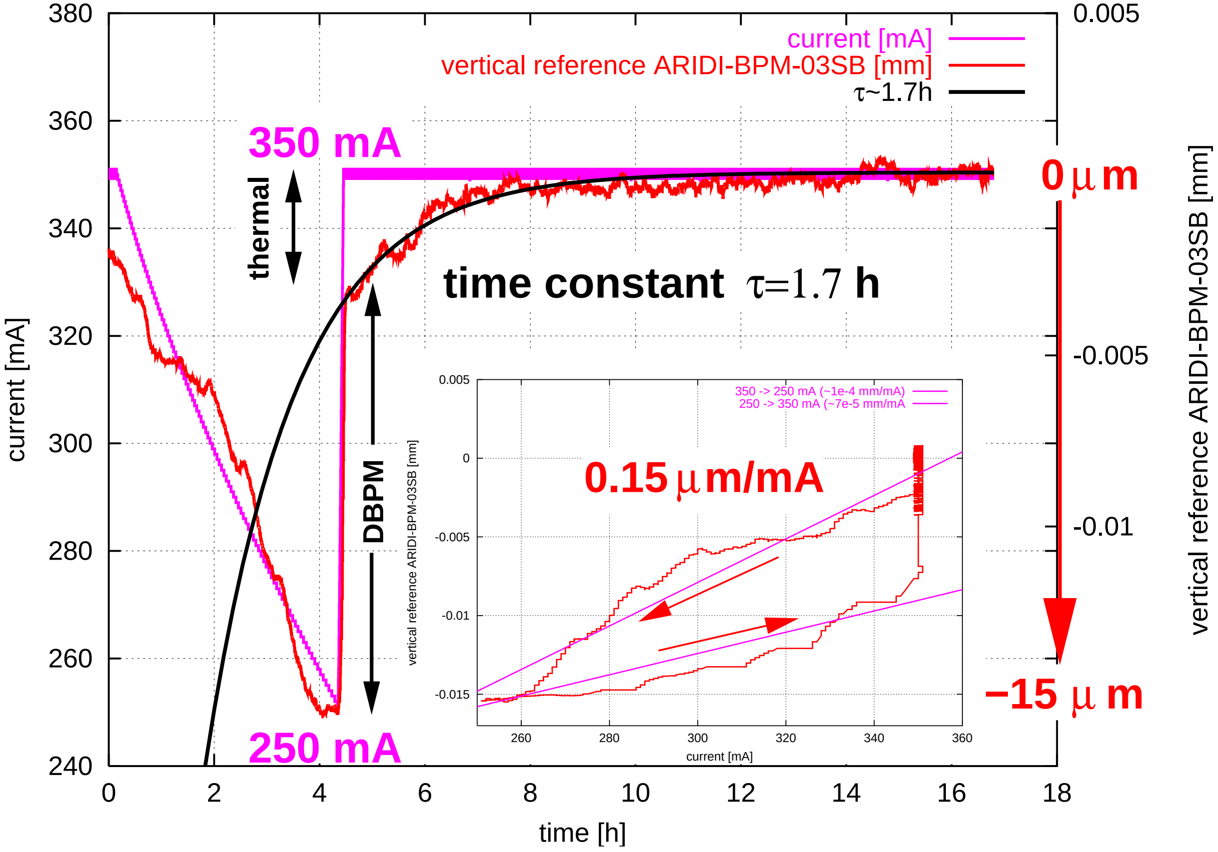
Alternative: Move the XBPM itself to calibrate the photon beam position reading, but:

One reason: XBPM feedback !

Calibration using machine bumps is preferred to calibration using motors as it is a tool to detect *alignments*.

MEDIUM TERM STABILITY - Top-up III (*SLS*)

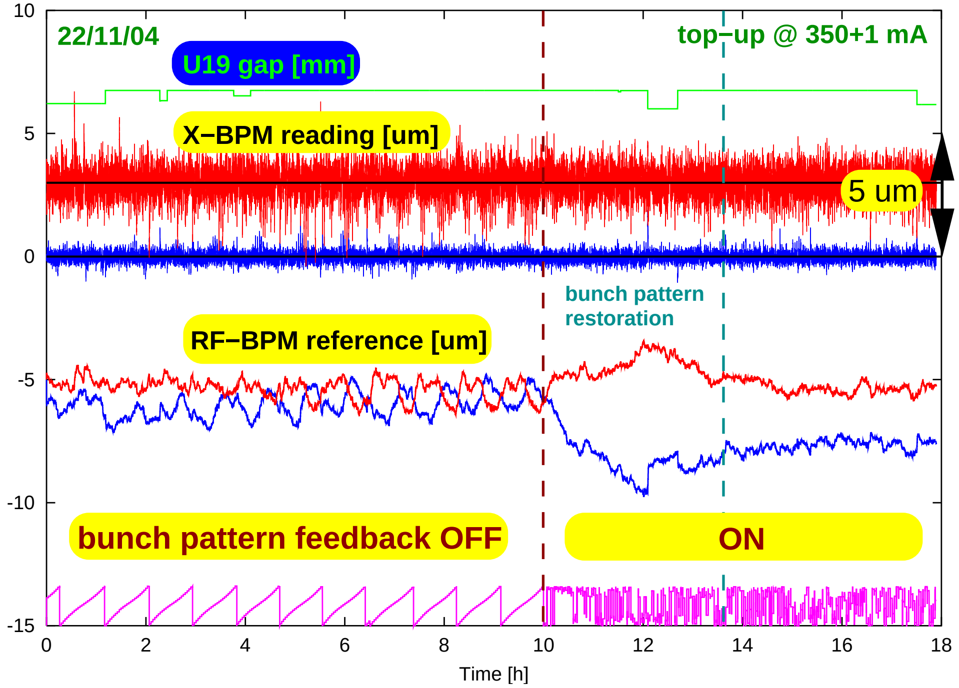
- Change of the vertical BPM reference within the X-BPM feedback loop for decaying beam operation (0-4 h) and “Top-up” (Time constant for getting back to thermal equilibrium τ=1.7 h):

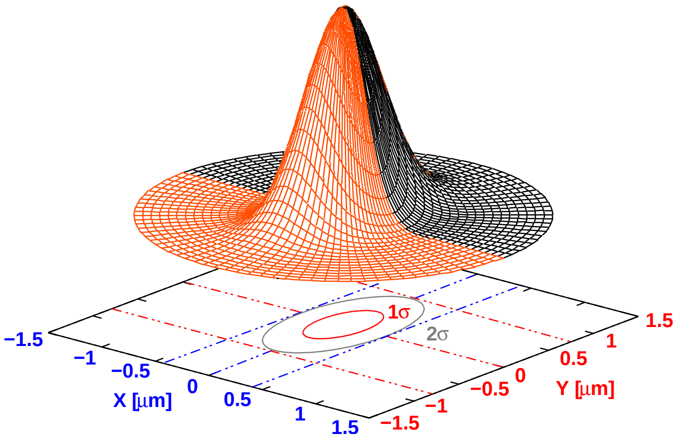


- Large (≈0.1 μm/mA) contribution originating from current dependence of digital BPMs

MEDIUM TERM STABILITY - X-BPM & Bunch Pattern Feedback *(SLS)*

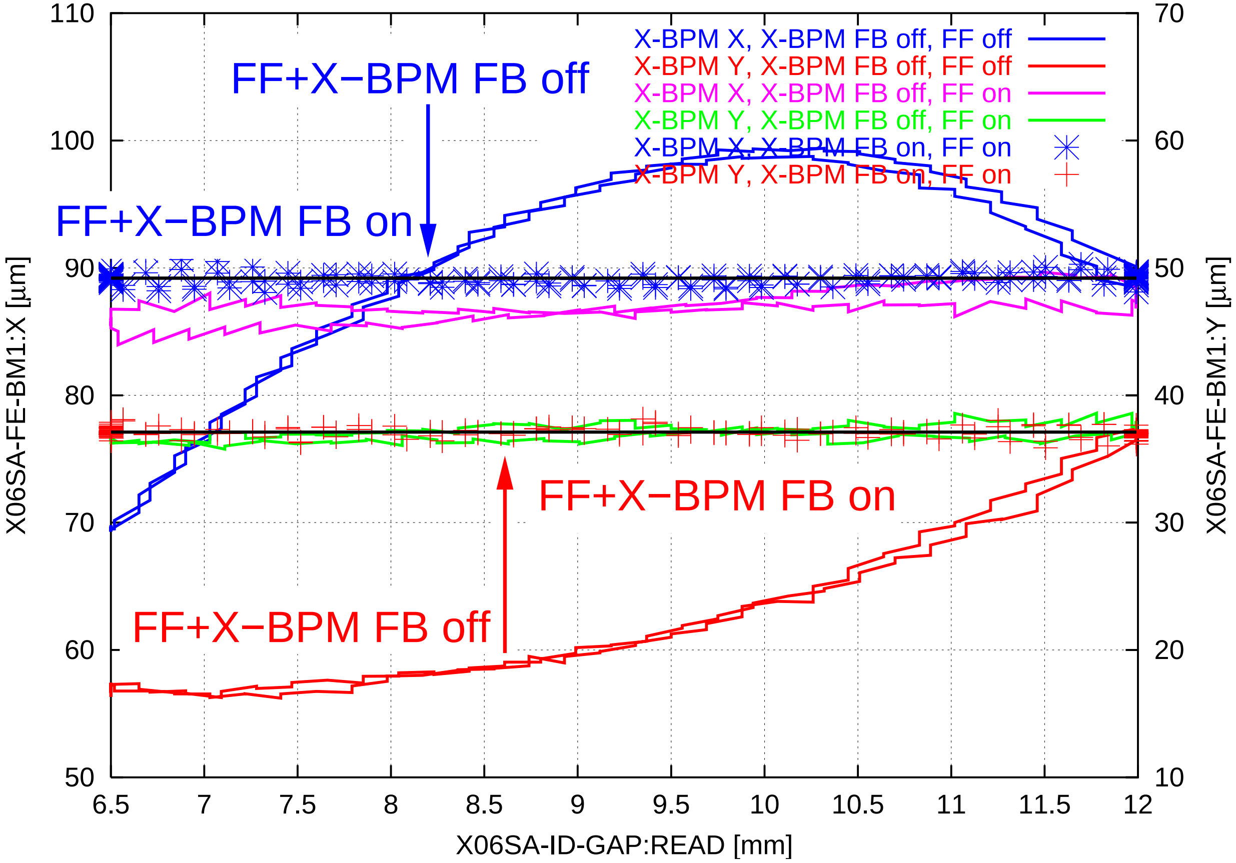
- The bunch pattern feedback maintains the bunch pattern (390 bunches (≈1 mA)) within <1 %
- The X-BPM feedback (**slave**) stabilizes the photon beam (Example beam line **6S**: 1 X-BPM ≈9 m from source point (**U19**)) by means of changes in the reference orbit of the fast orbit feedback (**master**) to ≈0.5 μm for frequencies up to 0.5 Hz.
- X-BPM feedbacks are operational @ the ID beam lines **4S**,**6S**,**10S** (1 X-BPM⇒angle only) and the dipole beam lines **2DA**,**7DA** (2 X-BPMs⇒angle & position).



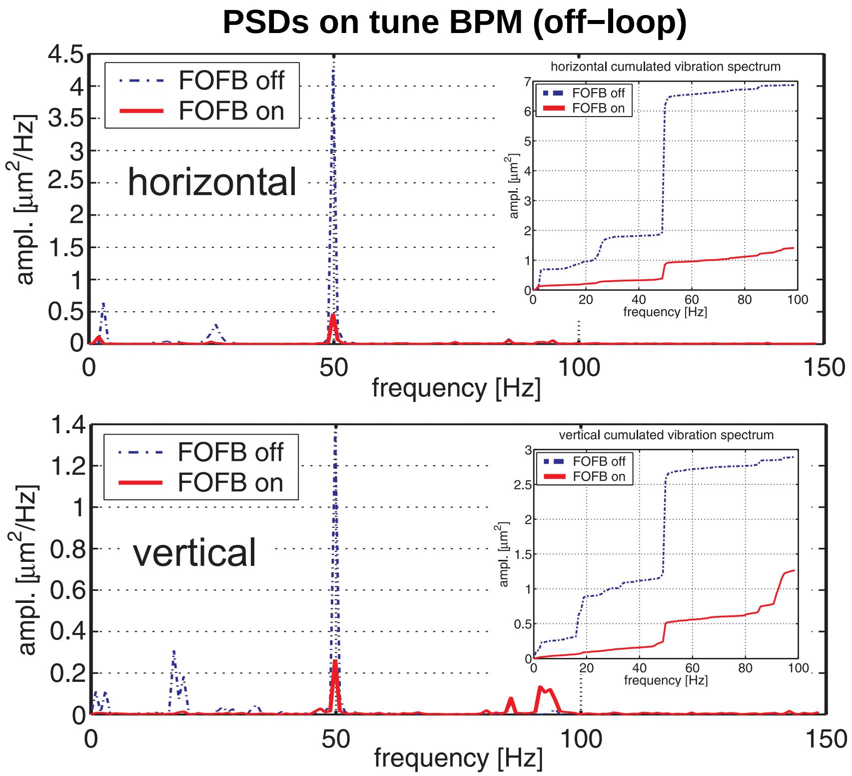


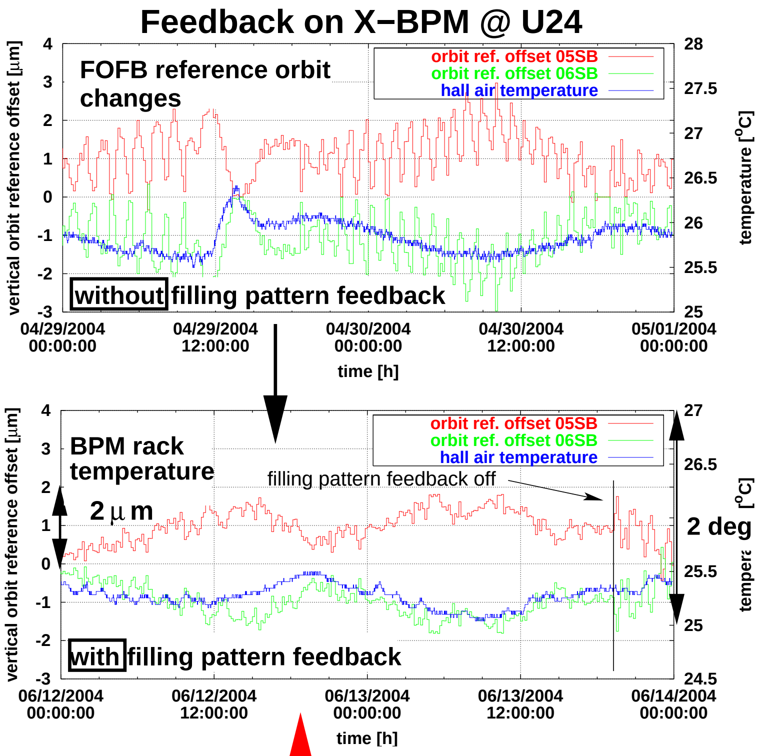
MEDIUM TERM STABILITY - Feed Forward & X-BPM Feedback (*SLS*)

- The feed forward tables (here for the in-vacuum device **U24**) ensure a constant X-BPM reading for the desired gap range (here 6.5-12 mm) within a few μm. The remaining distortion is left to the X-BPM feedback



SHORT/MEDIUM TERM STABILITY (*SLS*)

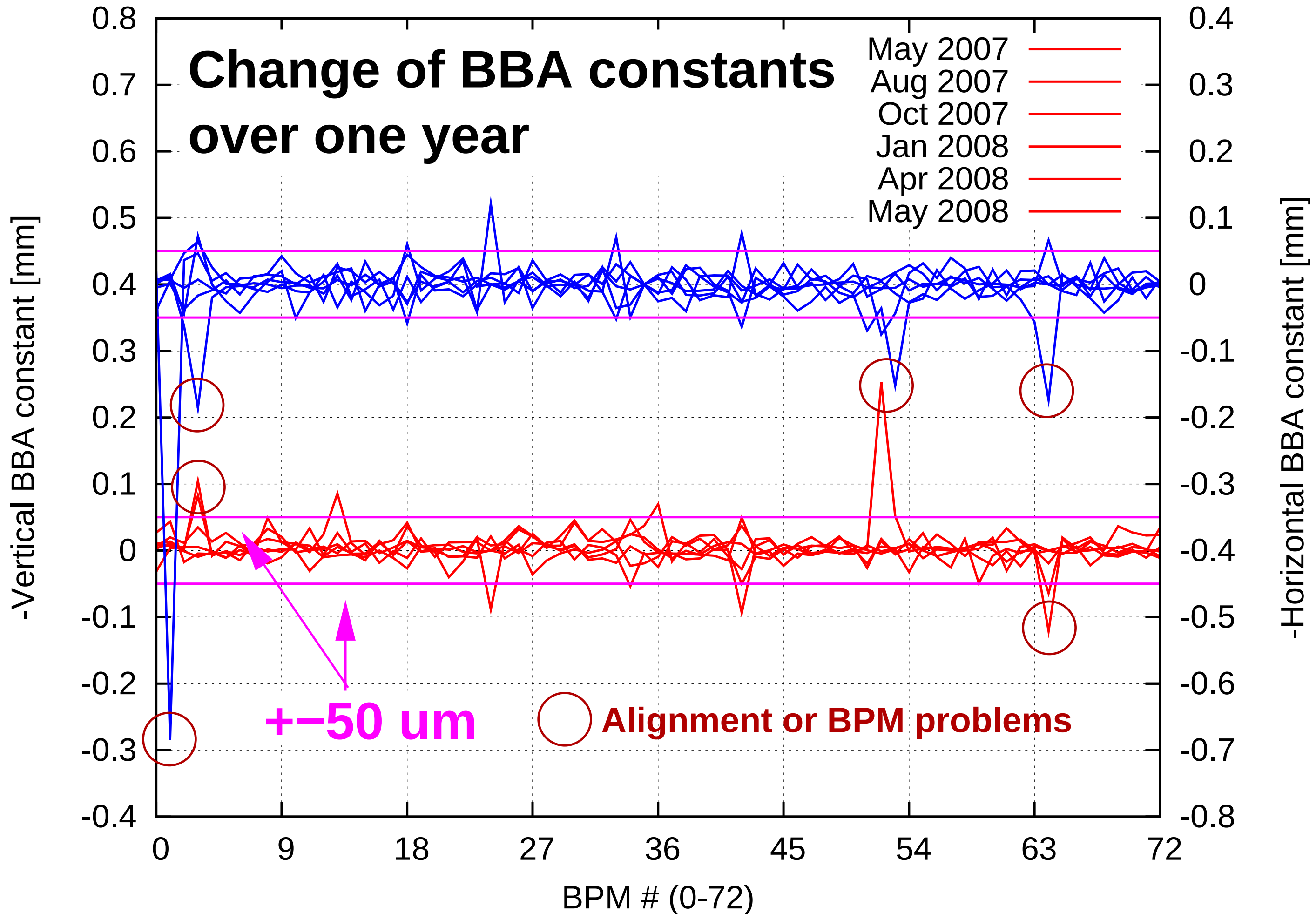




	horizontal		vertical	
FOFB	off	on	off	on
1- 100 Hz	**$0.83\ \mu m \cdot \sqrt{\beta_x}$**	**$0.38\ \mu m \cdot \sqrt{\beta_x}$**	**$0.40\ \mu m \cdot \sqrt{\beta_y}$**	**$0.27\ \mu m \cdot \sqrt{\beta_y}$**
100-150 Hz	$0.08\ \mu m \cdot \sqrt{\beta_x}$	$0.17\ \mu m \cdot \sqrt{\beta_x}$	$0.06\ \mu m \cdot \sqrt{\beta_y}$	$0.11\ \mu m \cdot \sqrt{\beta_y}$
1-150 Hz	$0.83\ \mu m \cdot \sqrt{\beta_x}$	$0.41\ \mu m \cdot \sqrt{\beta_x}$	$0.41\ \mu m \cdot \sqrt{\beta_y}$	$0.29\ \mu m \cdot \sqrt{\beta_y}$

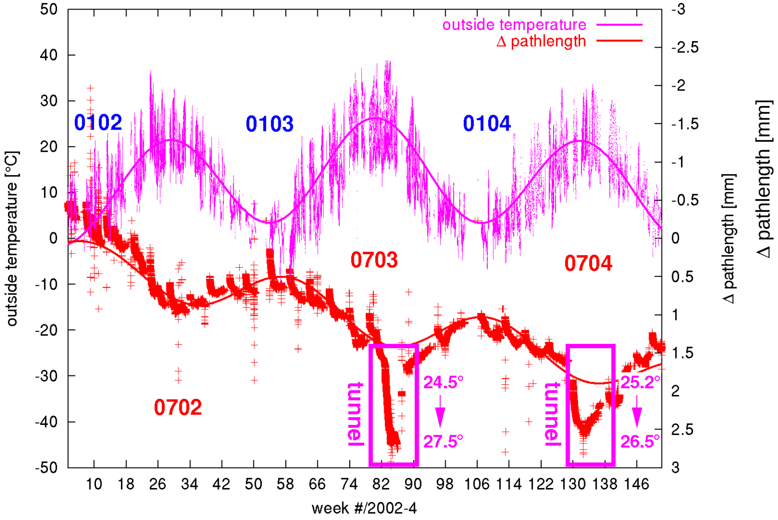
1Hz X−BPM feedback changes the reference of BPMs adjacent to IDs within the FOFB loop in order to stabilize the photon beam position at the X−BPMs −> cascaded feedback

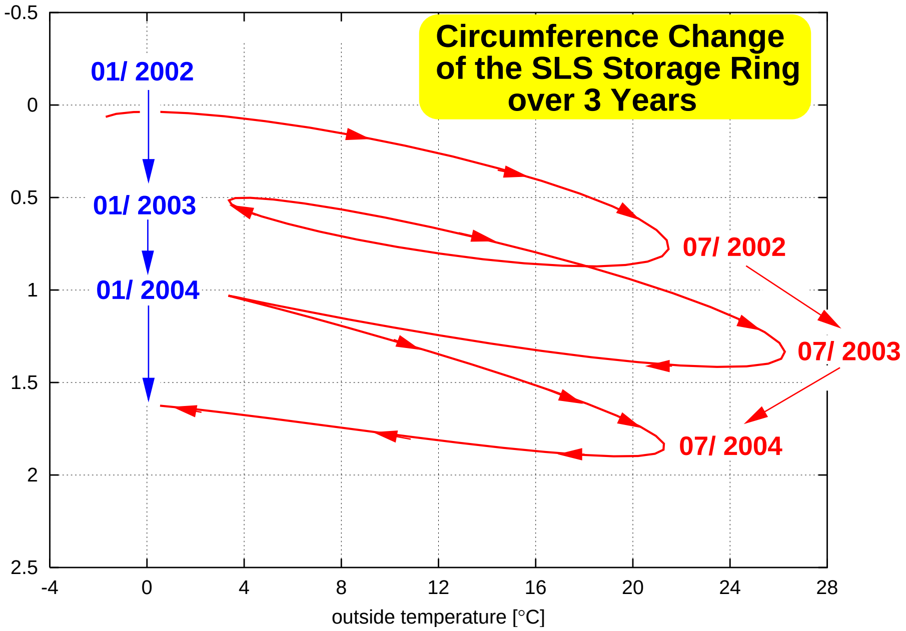
LONG TERM STABILITY - BBA Measurements over 1 Year (*SLS*)



LONG TERM STABILITY - Circumference I (*SLS*)

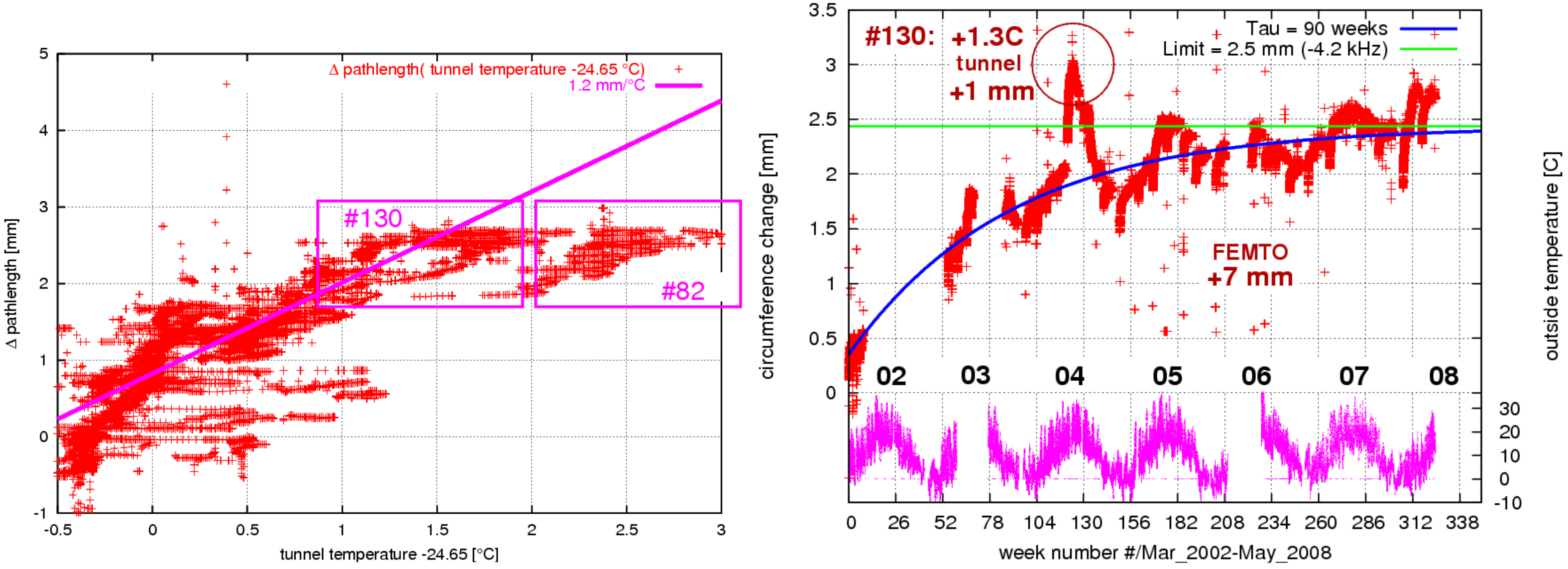
- Circumference change and outside temperature over 3 years of SLS operation (left plot)
- Fitted circumference change over 3 years of SLS operation (⇒ Δ circumference ≈ 2 mm) as a function of the fitted **outside temperature** (right plot)





- Severe problems with the cooling capacity of the SLS during the hot summer 2003 (#82)! Again “scheduled” problems in 2004 (#130) due to the cooling system upgrade!

LONG TERM STABILITY - Circumference II (*SLS*)



- Stabilization of the **tunnel temperature** to $\approx \pm 0.1^\circ$ is needed to guarantee sub-micron movement (see linear fit in left plot) !
- Change of the circumference over 6 years of SLS operation is saturating with an exponential time constant of $\tau = 90$ weeks and an asymptotic circumference change of 2.5 mm (the change due to installation of FEMTO chicane has been removed, see fit in right plot).

CONCLUSIONS & OUTLOOK

- Short and medium term sub-micron orbit stability can be achieved in 3rd generation light sources.
- Fast orbit feedback systems and "top-up" operation are key ingredients to reach this level of stability.
- The stability of beam line components apart from X-BPMs has not been discussed.
  But it is evident that the achieved stability needs to be maintained throughout the beam line. To this end fast feedbacks on monochromators and other optical components have the potential to improve the stability of the beam line optics considerably.
- **Future**: Fast orbit feedbacks will have to control betatron coupling / dispersion by means of skew quadrupoles if % or even sub-% beam size stability is required (SLS: 36 skew quadrupoles in order to make changes coupling transparent).
- **Vision:** High bandwidth orbit feedbacks and bunch-bunch feedbacks could merge into one system :-)